SCIENCE AND TECHNOLOGY

JET PROPULSION

Journal of the
AMERICAN ROCKET SOCIETY
Rocketry . . . Jet Propulsion Sc . . . Astronautics

STACKS

VOLUME 26 AUGUST 1956 NUMBER 8

The Use of Nuclear Radiation in Combustion Research . . . . . *Martin E. Gluckstein, Richard B. Morrison, and John V. Nehemias* 637

Improved On-Off Missile Stabilization . . . . . *Robert W. Bass* 644

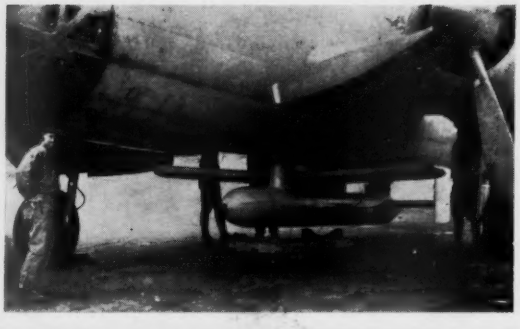
Application of Hydraulic Analog Method to One-Dimensional Transient Heat Flow . . . . . *Eldon L. Knuth and Emerson L. Kumm* 649

Observations on the Irregular Reaction of Solid Propellant Charges . . . . . *Leon Green, Jr.* 655

Ten Years of Project SQUID—A Bibliography 660

Special Paper

Japanese Guided Missiles in World War II . . . . . *Martin Caidin* 691



WW II J-go put Japan in guided missile business . . . p. 691

Jet Propulsion News 681

ARS News 699

New Patents 704

New Equipment and Processes . . . 708

Book Reviews 710

Technical Literature Digest . . . 714

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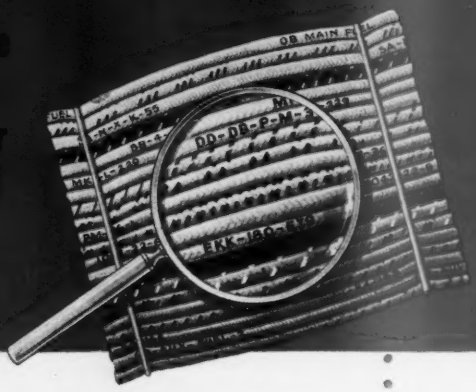

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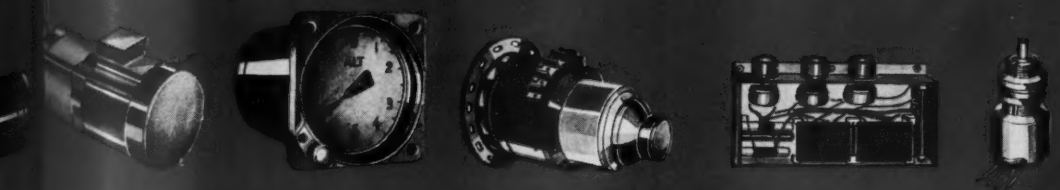

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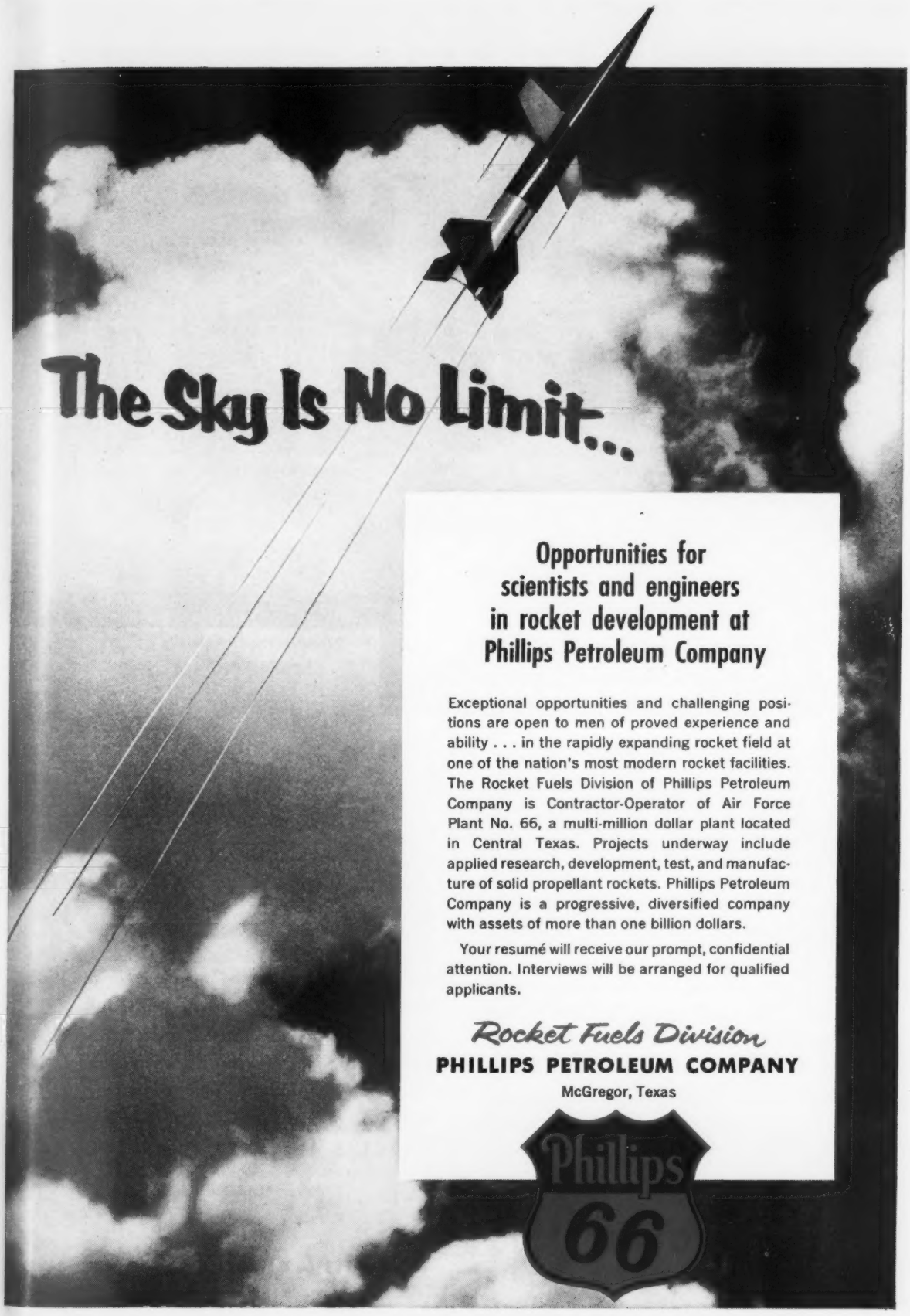
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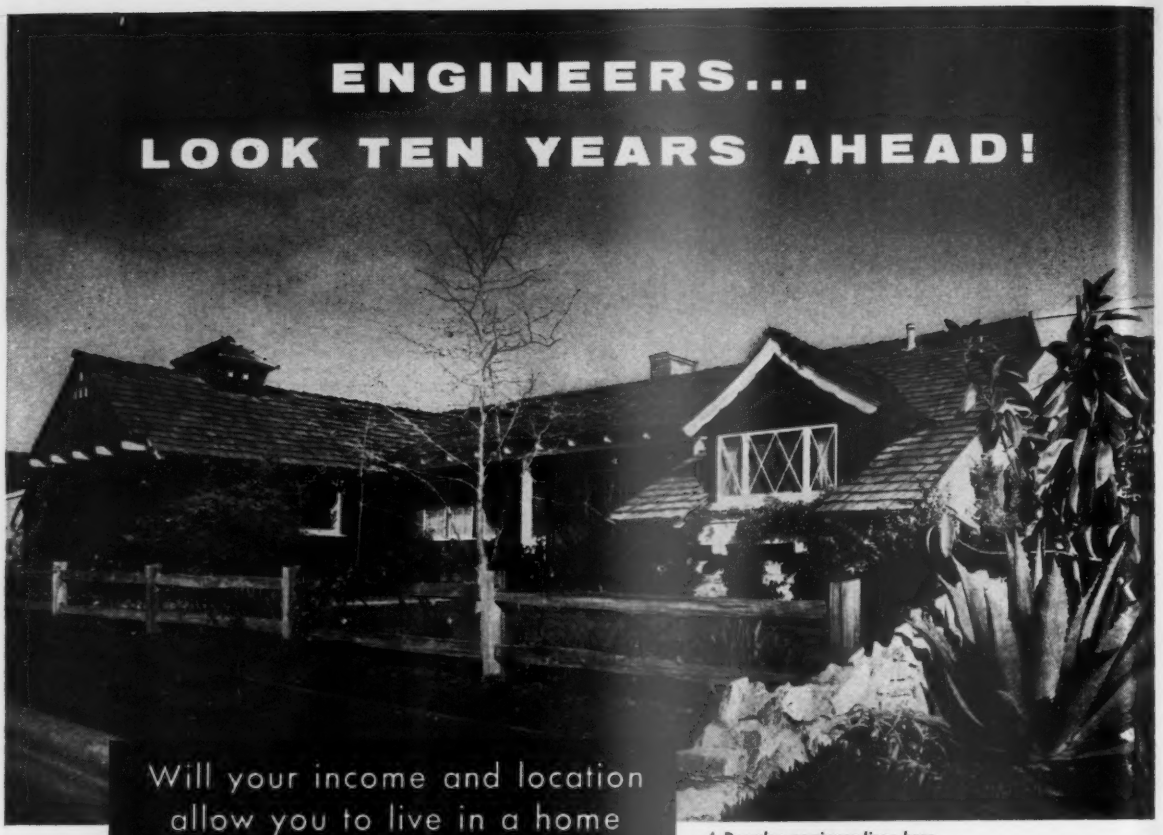

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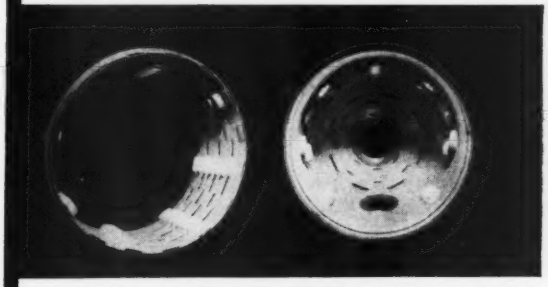

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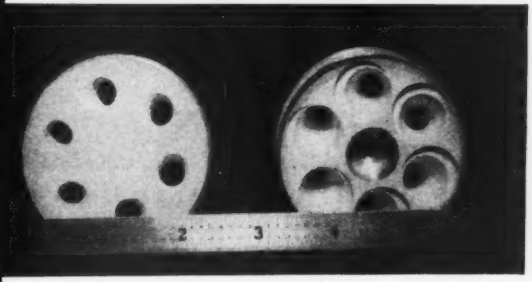

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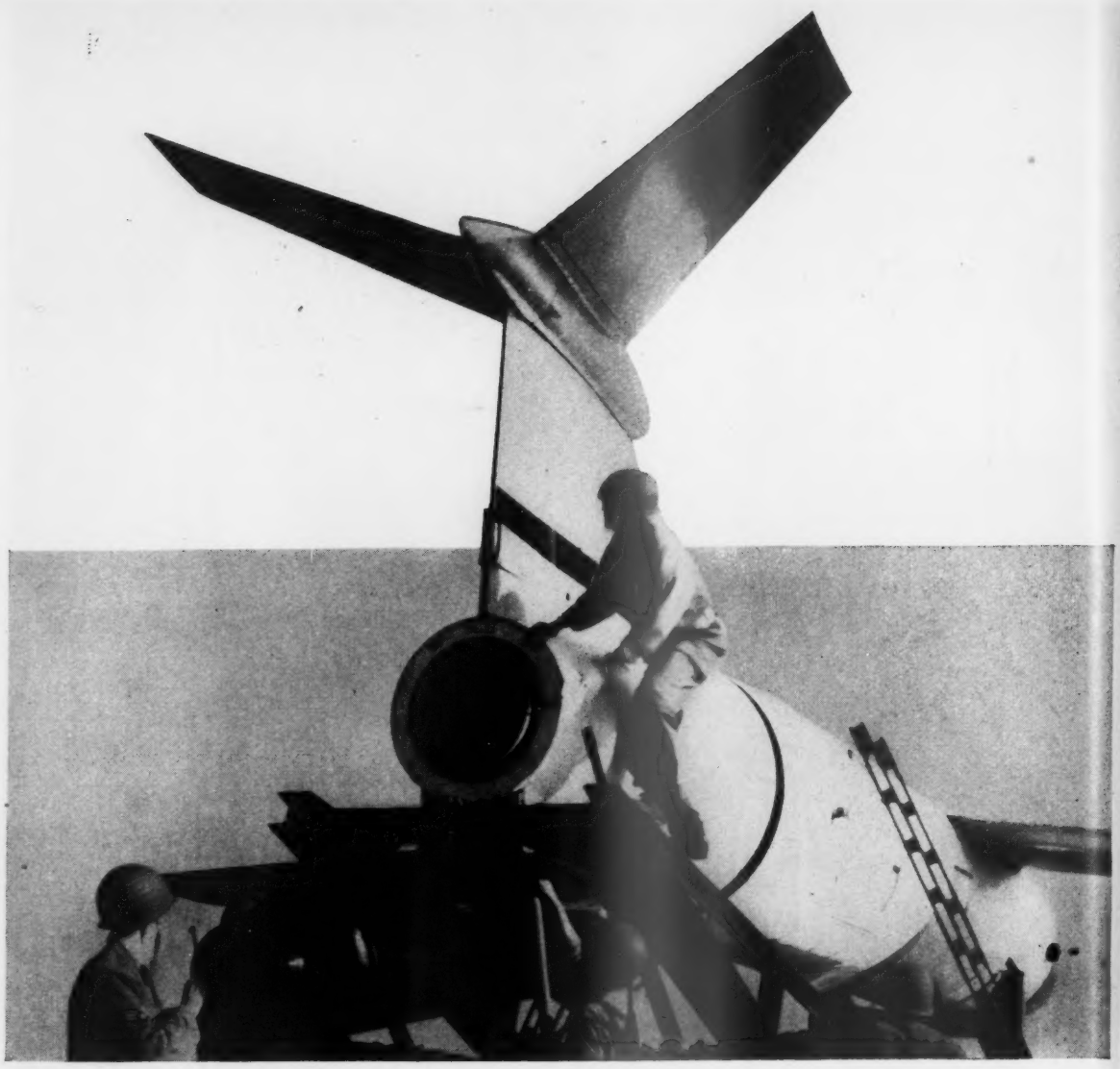

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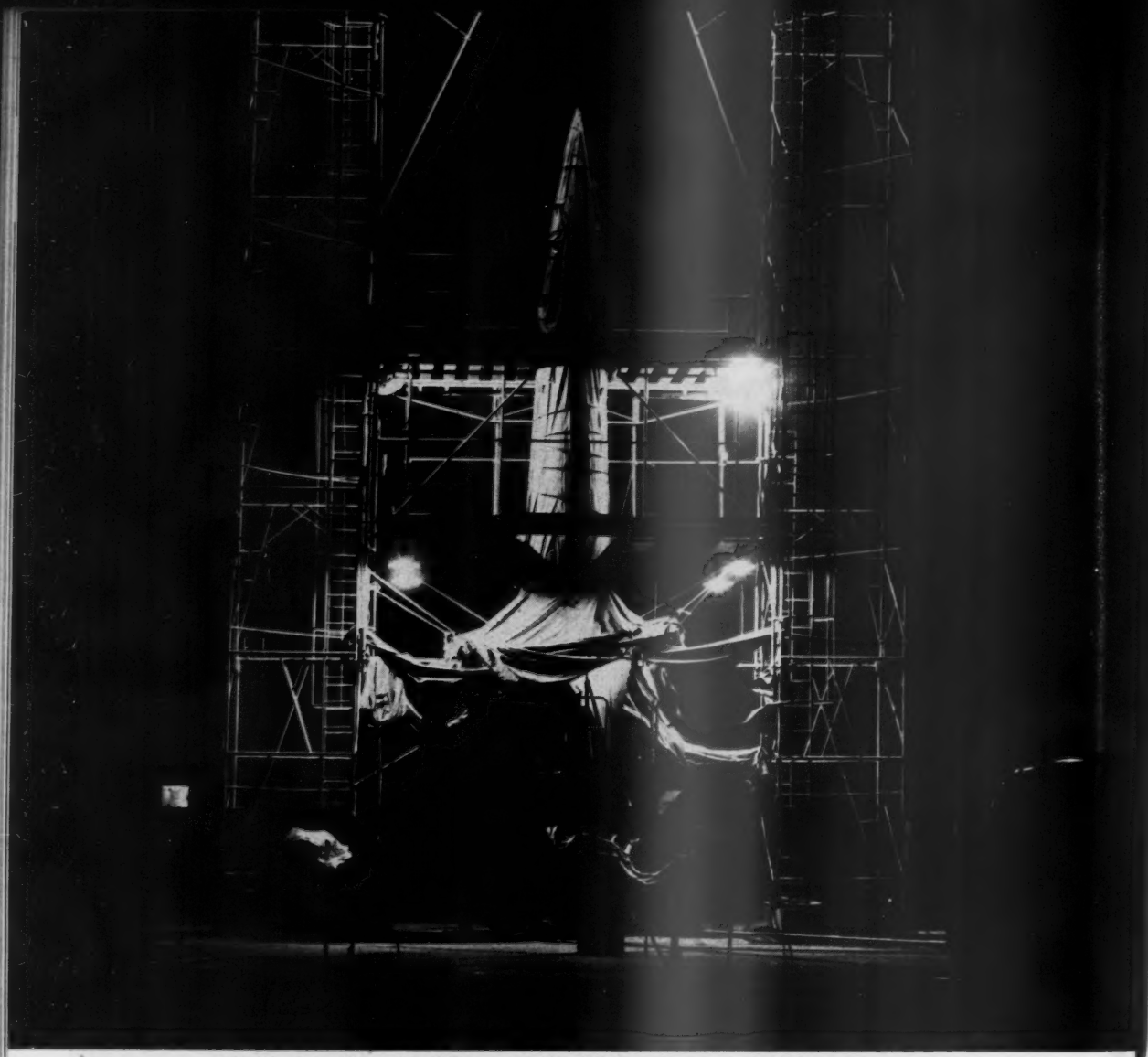

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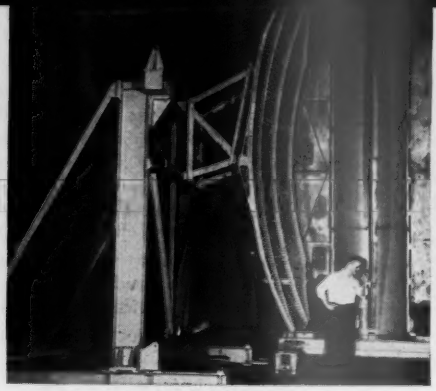

COMMUNICATIONS

HYPERSONICS

At General Electric, George F. Metcalf reports:

New Department to Help Solve Complex Defense System Problems

GEORGE F. METCALF, is General Manager of General Electric's new Special Defense Projects Department, located in Philadelphia, Pa. Mr. Metcalf has had extensive management experience in the military electronics field, both in Government Service and in the General Electric Company's Electronic Division.

Realizing the increased complexity of some of the nation's current defense system problems, General Electric has formed the Special Defense Projects Department. The new department will act as a Company focal point for large, highly complex missile projects. Headquarters for the new department will be located near Philadelphia, Pa. This new department has responsibility for large defense systems that require the combined research, development, and manufacturing resources of many of General Electric's operating departments and laboratories.

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The Special Defense Projects Department is making significant contributions to America's defense program by focusing the wide range of specialized talents of General Electric on highly complex defense system problems. Section 224-4, General Electric Co., Schenectady 5, N.Y.

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Dr. S. H. Browne (left), Assistant Director of Research, J. H. Carter, Associate Director of Research and Staff Scientists P. L. Taulbee and E. V. Stearns discuss weapon requirements for defense of continental United States.

SYSTEMS PLANNING

▲ ▲ ▲

the basic approach to missile development

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AUGUST 1956
VOLUME 26 NUMBER 8

JET PROPULSION
Journal of the
AMERICAN ROCKET SOCIETY

Editor-in-Chief
MARTIN SUMMERFIELD

The Use of Nuclear Radiation in Combustion Research

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The interaction of nuclear radiation with fuel-oxidant systems may cause increased rates of chemical reaction. Based on simple models for the interactions and the controlling rate processes, it is shown that change in over-all reaction rate should be dependent upon the energy and activity of the radiation source. Only beta and alpha emitters are considered since, for gas phase reactions or for reactors of relatively small size, they are the more efficient sources. The problems involved in the use of radioactive materials in combustion research are discussed and, in particular, criteria for compatible design are established. The possible application of this technique to improve the performance of combustion devices is discussed in the light of the difficulties and results of experimental work in this field.

Introduction

THIS paper presents some of the experiences of the authors in the use of nuclear radiation in combustion research, some pertinent experimental design considerations, and possible application to combustion devices. Discussion will be limited to the problems of design, handling, and application of the radioactive materials, since some of the results have been reported elsewhere (1, 2).[4]

Programs of this type gained impetus under the fission products utilization program of the United States Atomic Energy Commission. The use of radiation from these materials to promote chemical reactions, including those in combustion devices, has been considered. However, these studies may also offer an opportunity to gain insight into the fundamental processes occurring in combustors.

Only alpha and beta sources will be considered in this paper. Generally speaking, gamma radiation in the Kev and Mev range is too penetrating to be useful in work of this type, but must be considered since it is most difficult to shield and hence a primary health physics problem.

Discussion

To determine the effect nuclear radiation might have on combustion systems, it is first necessary to consider some of the details of the possible mechanism and kinetics of oxidation reactions and the mechanism of the interaction of radiation with the reaction system. If one considers the oxidation of a hydrocarbon, there is abundant evidence that the reaction does not proceed according to the over-all stoichiometric equation, but through a series of consecutive or simultaneous reactions involving free radials and atoms, such as O, OH, CH_3, C_2H_5; and the various partial oxidation products of the hydrocarbon, such as CO, aldehydes, ketones; and transitory materials, such as peroxides; as well as the original materials (4, 6, 7). It is sufficient for the development of a consistent physical model to consider the reactions in general, without recourse to any specific system.

For any chemical reaction

$$M + N \rightarrow MN^* \rightarrow MN \quad [A]$$

where MN is the product and MN^* the activated complex, the rate of reaction may be expressed as

$$r = k_r C_M C_N \quad [1]$$

where r is the rate of formation of MN; C_A, C_B, the concentration of M and N and k_r, a reaction rate "constant" in consistent units. The constant k_r is usually expressed by the Arrhenius equation as

$$k_r = A \exp(-E_T/RT) \quad [2]$$

where A is the "frequency factor" and $\exp(-E_T/RT)$ is the fraction of molecules in the given system of energy equal to or greater than E_T. The value of the constant A is determined from the partition functions for M, N, and MN^* and is a function of the temperature and the atomic or molecular constants associated with the particular species involved in the reactions. One may, however, vary the fraction of active molecules (i.e., those of energy equal to or exceeding E_T) by providing an external source of high energy molecules or by generating them within the system. One method of generating additional active species is to subject the reaction mass to ionizing (nuclear) radiation.

The specialized development of exact relationships for the interaction of radiation and matter is beyond the scope of this paper. It is only necessary to consider the gross effect of such interactions. Experimentally, it has been shown that alpha, beta, or gamma radiation, when passing through a gaseous medium, induces ionization and reactions of the type

$$O_2 \rightleftharpoons 2O^* \quad [B]$$

or generally

$$MN \rightleftharpoons M^* + N^* \quad [C]$$

The asterisk indicates that the energy of the species generated by the interaction is higher than energy which is associated with the thermally produced species. On the average, each interaction expends 33 electron volts to form an ion pair (such as $M^* + N^*$ above). Since the activation energy E_T for most reactions is of the order of 10–100 K cal/mole (0.42 to 4.2 ev per molecule), the value of 33 ev is in excess of the activation energy and, therefore, the species produced by the interaction are active insofar as reaction is concerned.

Presented at the Nuclear Engineering and Science Congress, Cleveland, Ohio, Dec. 12–16, 1955.

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[3] Research Associate and Health Physicist, Fission Products Laboratory.

[4] Numbers in parentheses indicate References at end of paper.

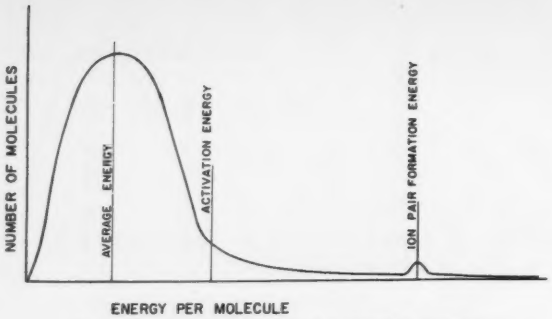

Fig. 1 Energy distribution in a reacting system

Fig. 1 shows diagrammatically the energy diagram for gaseous reaction system in the presence of an ionizing source.

The effect of radiation on the reaction rate constant may be expressed mathematically as

$$k_r' = A[\exp(-E_T/RT) + f] \quad [3]$$

where f is the fraction of radiation induced active species. The ratio of the reaction rates with and without radiation should be

$$r'/r = 1 + \exp(E_T/RT) \cdot f \quad [4]$$

To evaluate f it is necessary to know the energy, type of the radiation, the total activity, and a factor based on the geometry of the systems. The value of f will be given by

$$f = \phi(CE/33)(M \times N_0)^{-1} \times 3.7 \times 10^{10} \quad [5]$$

where C is the activity of the source in curies; E its energy in electron volts; M the molar flow rate, mole-sec^{-1}; N_0 Avogradro's number; and ϕ factor for geometry, secondary radiation, and other factors mentioned above.

As an example consider an experimental combustor 3 cm in diam and 30 cm long, operated at one atmosphere pressure. It is desired to locate the radioactive material in the wall of this reactor. The flow rate of fuel and oxidant is 0.01 mole per sec and it may be assumed to have the same absorptive properties as air. The source is to be a 1- Mev beta emitter. It has been calculated from Equation [4] that f must have a value equal to or greater than 10^{-5} to be effective in accelerating combustion. To compute f, one must first evaluate ϕ. For 1 Mev beta radiation, the range is about 300 cm in air. To estimate ϕ, it is assumed that the active species formed have a life of 1 microsec and therefore only interactions in the reactor volume need be considered. Since the diameter of the reactor is 1 per cent of the range, at most 1 per cent of the primary radiation is effective. However, due to the spherical distribution of the radiation, some particles will pass out the ends of the reactor and be ineffective. Neglecting reflection and secondary radiation, ϕ will be about 10^{-3}. From Equation [5], $C = 1.3 \times 10^3$ curies.

Consider the same design using alpha radiation of about 5 Mev. For this radiation, the range is about 3 cm and ϕ will be at least 0.1. From Equation [5], C will be about 3 curies.

One may not conclude that for this application the alpha source would be more desirable than the beta. The ultimate selection of the source will depend on the availability, handling difficulties, chemical stability, hazard, and costs. Of these, those factors which affect health and safety are most important. Some of the health physics aspects of this type of work are presented in the next section.

Health Physics

Personnel working with radioactive materials are exposed to two distinct types of hazards: (a) external radiation and (b) contamination. It is important that these two types of radiation hazards be separately evaluated for each proposed experiment using radioactive materials.

A External Radiation

Serious instances of injury due to external radiation occurred in the early days of work in this field. Within 30 days of the discovery of x-rays by Roentgen in 1896, one of his co-workers reported hand dermititis so acute that medical aid was required. Another early radiation injury involved Henri Becquerel himself. Several years after his discovery of radioactivity he had occasion to carry a tube containing a radium salt in his vest pocket for several days. An ugly red lesion developed on his abdomen which did not heal for several months and left a permanent scar.

The absorption of ionization radiation by living tissue causes injury to individual living cells. The injury is manifested as the malfunction or death of some of the irradiated cells, which, according to the severity of the exposure, may subsequently cause clinical symptoms or death of the organism. However, even a lethal dose of radiation causes the victim no immediate pain or discomfort. Death does not follow immediately, but results from buildup of degenerative toxins and lowered resistance to trauma and infection.

Although the cellular destruction caused by ionizing radiation is characteristically similar for all known types of ionizing radiation, the degree of localization, and thus the severity, vary according to the rate at which the type of radiation in question is absorbed. External alpha radiation, for instance, which is the only radiation emitted by polonium-210, is totally absorbed in the loamy, surface layer of epithelial tissue. Serious radiation injury from an external exposure to alpha radiation is quite unlikely.

Beta radiation, which is the only radiation emitted by palladium-109, penetrates several millimeters of tissue. Severe blistering and burns, which heal very slowly, result from local overexposures to external beta radiation. Gross effects on total metabolism from external beta radiation can be observed only if a large part of the body is exposed or the exposure is very large.

Gamma radiation, which is emitted by gold-198 in addition to beta radiation, produces effects throughout the body because of the highly penetrating nature of the radiation. Gross metabolic effects, such as reductions in white blood cell levels, rather than localized injury, result from severe overexposure.

The risk of personal injury from external radiation may be minimized by judicious manipulation of three physical parameters: distance, time, and shielding.

A radioactive material emits its radiation in all directions. As the distance from the source increases, the radiation flux decreases. For a point source, this rate of decrease is inversely proportional to the square of the distance. Radiation exposure to personnel can be reduced most simply by minimizing operations which require approaching the radioactive material. The use, when possible, of tongs and other remote control manipulators exemplifies this principle.

When it is essential that an operation be performed in such a way that high exposure rates are experienced by personnel, exposure can obviously be best minimized by expediting the operation in every possible way to the time spent in the intense radiation field.

When the optimum use of distance and time cannot reduce exposures to a tolerable level, the use of shielding materials becomes necessary. As ionizing radiation penetrates matter, interactions occur, energy is lost, and total intensity is reduced. The interposition of matter (such as water, concrete, lead) between the radioactive material and operating personnel thus results in reduced radiation levels.

Alpha particles may be completely absorbed by a sheet of heavy paper, beta particles by a few centimeters of lucite. Gamma radiation, on the other hand, is absorbed exponentially. That is, if a certain thickness reduces the radiation from 100 to 10, twice that thickness would reduce it from 100 to 1. Thus no thickness of shielding will completely absorb

gamma radiation. It becomes necessary to think in terms of radiation levels to acceptable values.

In the ideal case of absorption of a perfectly collimated beam of radiation, the degradation of energy, scattering, and production of secondary radiation can be ignored, as any interaction of these types would completely remove the interacting particle or photon from consideration. In practical cases, however, the build-up of secondary radiation is an important consideration.

The gamma radiation intensity at a point in an absorber consists of primary gamma photons, the photons of degraded energy resulting from Compton scattering, secondary electrons (photoelectrons, Compton electrons, and electron pairs), and the electromagnetic radiation produced by the absorption of these electrons. The secondary radiation is, in general, more rapidly attenuated than the primary gamma radiation.

The radiation intensity I at a point behind a shield of thickness X is computed from the relationship

$$I = I_0 \beta^{-\mu X} \quad [6]$$

where I_0 is the radiation intensity at the same point with no shielding present, β is the buildup factor, and μ the absorption coefficient. β and μ can be evaluated from the literature (3, 5). These two quantities depend upon absorber material, thickness, and radiation energy.

B. Contamination

When a radioactive element enters the body, it is distributed, metabolized, and utilized in the same manner as the same element would be in the nonradioactive state. When these processes lead to incorporation into the body structure by deposition in the bone or by other means, localized internal radiation damage may ensue. As in the case of external radiation injury, no pain or discomfort is felt by the victim until some time after the ingestion. This delay in the appearance of observable symptoms renders the task of diagnosing the ultimate cause and evaluating potential injury from an exposure exceedingly difficult.

Radioactive material may enter the body by three main routes: inhalation, ingestion, and injection. Airborne particles or radioactive gases may be inhaled. Radioactive material unconsciously or absent-mindedly transferred to food, cigarettes, or pencils may find its way into the body through the mouth. The accidental puncturing of protective clothing and the skin during an experiment may inject radioactivity directly into the blood stream.

The mechanism of injury is the same whether the radiation is external or internal. The radiation characteristics which determine the degree of internal radiation hazard are quite different from those previously discussed for external radiation.

Alpha radiation is completely absorbed in a small volume of tissue, leading to severe localized tissue damage, sarcoma, and other related injuries. If an equal amount of beta radiation energy is absorbed in the body, it would be distributed throughout a much larger tissue volume. Tissue damage in this case is more diffuse but still localized. Internal gamma radiation would penetrate still further and would be expected to produce little local injury—only gross total body radiation damage.

The risk or personal injury to inhaled or injected radioactive materials can be minimized by careful experimental design, continuous radiological monitoring, and good housekeeping procedures.

The initial design of an experiment must take into account the degree of contamination involved. Good experimental design should minimize the possibility of incidents which could speed radioactive contamination, as well as include safe procedures for use in the event such a mishap occurs.

Electronic radiation monitoring devices can be kept in continuous operation throughout an experiment. They can sound the alarm when a predetermined "safe" level of radioactivity is exceeded and set emergency procedures into operation. A further radiological check of workers' hands, feet, and clothing as they leave the laboratory protects the workers and prevents the spread of radioactive material outside the laboratory.

The procedures involved in keeping a laboratory radiologically clean are mostly common sense. No dust or dirt are allowed to accumulate. Waste is disposed of before large amounts pose a radiation problem. Smooth, easily cleaned surfaces are used where possible. Otherwise, cheap and removable surfacing material is used.

Special Design Considerations

The most important single factor in the design of equipment to utilize nuclear radiation in combustion research is that the experimental procedures be compatible with the requirements of radiological safety. It is necessary that all stages of planning and execution of the research program be made with the assistance of competent radiological safety personnel, since the research worker is often not able to objectively analyze the potential radiological hazard in a particular design or operation.

The initial step in equipment design is to prepare a preliminary sketch of the equipment showing source location and other pertinent details, and to list the important assembly and data taking operations. It is then necessary to calculate the approximate activity required for various possible types of sources, as shown in the Discussion. Each potential source material must then be examined in detail. It is first necessary to ascertain whether the required activity can be obtained, and at what cost. The half life may be a factor from both the experimental and health standpoint. It is important that the decay scheme of the isotope be examined to be certain that the radioactivity of the daughter products of the primary source are not neglected. Experimentally, it is desirable that the half life of the source be long compared to the time required for a data run, so that the activity is nearly constant throughout the operation. As a safety consideration, it is desirable that the half life be relatively short so that, in the event of a catastrophe (such as loss of the source by explosion, melting, or oxidation), the area will not remain contaminated for long.

Chemical and physical properties must next be considered. Chemically, it is desirable that the source be inert chemically and metabolically. In the event the material is metabolized extreme caution in handling must be exercised to prevent, contamination and this requirement often will not be compatible with the other experimental requirements. Materials which are to be in contact with the flame should be chemically inert or should be encapsulated in a protective material. All materials in contact with flames should be cooled to prevent softening, attrition, or vaporization. The machinability of the material will be a factor for many applications, and it is important that adjacent components be fabricated of materials of similar properties to avoid thermal or mechanical difficulties.

The actual mass of the activity will often be quite small, and it will be necessary to support it on a carrier, in which case the radiological property of the carrier becomes important as a possible contaminant, in computing shielding requirements, and a possible contributor to the total effective radiation. Another important factor is the self-shielding of the source and any gamma radiation associated with it. The self-shielding characteristics will often require that the activity be increased to maintain the necessary effective ionization, and the latter factor presents the main external shielding problem.

All exhaust lines carrying combustion products must be provided with filters and must be monitored for contamination. In any operation where there is a danger of explosion,

Table 1 Radiological properties of sources

Source	Half life	Radiation type and energy		Daughter product	Principal hazards
Pd^{109}	13.1 hr	β^-	0.95 Mev	Ag^{109}	External radiation
Au^{198}	2.69 days	β^-	0.97 Mev	Hg^{198}	
		γ	0.411 Mev		
Au^{199}	3.3 days	β^-	0.32 Mev	Hg^{199}	External radiation
		γ	0.23 Mev (max)		
Cu^{64}	12.8 hr	β^-	0.57 Mev	Zn^{64}	Contamination
		β^+	0.65 Mev	Ni^{64}	
		γ	1.34 Mev		
Po^{210}	138.3 days	α	5.3 Mev	Pb^{206}	Contamination
		γ	0.8		
		$(\gamma/\alpha = 10^{-5})$			

the equipment should be located in an isolated area and emergency procedure preplanned and practiced.

Having selected a source, it is then necessary that the shielding and other safety requirements be examined with respect to the experimental needs. Special procedures for assembly and operation of the experimental equipment must then be devised. Each particular setup will present specific problems depending on the nature of the source and no general recommendations can be made. For illustrative purposes, we will consider the design of three specific installations which have been used or are in use at the present time.

Specific Applications

In this section, the general procedures outlined previously will be applied to three specific sources and applications. The materials to be considered are palladium-109, gold-198 and -199 (and copper-64), and polonium-210. The radiological properties of the materials are given in Table 1.

From the radiological safety standpoint these three source materials exemplify several different problems, which will be considered in turn.

A Polonium-210

Polonium-210 is an alpha emitter and decays to a stable isotope of lead. This material is extremely hazardous from the point of view of contamination, for several reasons.

1 It is an alpha emitter and can produce severe localized tissue damage if deposited in the body.

2 It is metabolized efficiently and incorporated into the bone structure on a long term basis.

3 It has a long half life (140 days) and can provide a continuous insult to tissue over a period of several years.

4 The extremely high particle energy (over 5 Mev) gives the parent nucleus such a recoil thrust that chunks of polonium are actually thrown into the air from a sample placed on a laboratory surface. Thus a whole room can become thoroughly and dangerously contaminated just by having a sample of polonium placed in it.

In view of these rather frightening aspects of this particular nuclide, one might well ask, when would the use of such a dangerous substance be justified? Some of its advantages should, therefore, be enumerated.

1 Because of its extremely short range in matter, essentially no protective shielding against external radiation is required.

2 The half life is long enough to permit leisurely, careful measurements in a fairly constant radiation field.

3 The extremely high rate of absorption makes possible efficient use of its tremendous energy within systems of reasonable size.

In practice, when these advantages are decisive, and the decision is made to proceed, the health hazards can be made negligible by suitable experimental design. Experiments with dangerous amounts of polonium-210 must be performed in completely enclosed, negative pressure systems, the exhausts of which are thoroughly filtered before release to the atmosphere. Only in this way can the extreme health hazards previously enumerated be obviated. With such precautions, work with high levels of alpha activity can be safely performed.

The polonium is to be used to study the mechanism of drag stabilized flames and the gross effects of radiation. Because of the excellent properties of polonium in regard to shielding and half life, it was felt that this material offers distinct advantages over other possible sources.

The equipment in which the polonium will be used is shown in Fig. 2. Polonium will be plated on a stainless steel flameholder and in this location can efficiently irradiate the reactor volume.

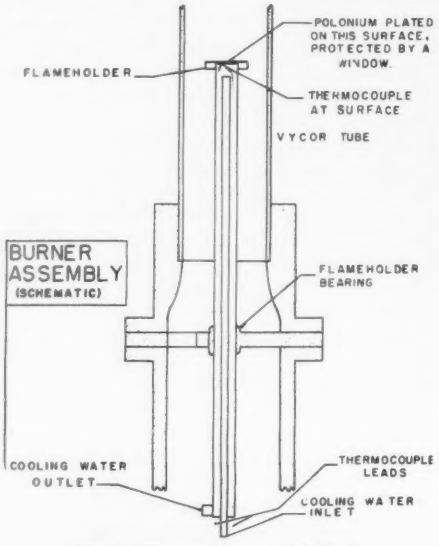

Fig. 2 Burner for use with Po^{210}

Due to the possibility of contamination, the active surface is sealed by a very thin stainless steel window and the entire setup located in a dry box. Assembly will be made by means of rubber gloves located as an integral part of the dry box and, since the range of the radiation is short, no shielding is necessary. By means of windows located in the box, it will be possible to observe the flames and photograph them without the necessity of developing special techniques.

B Palladium-109

Palladium-109 is a beta emitter and decays to a stable isotope of silver. In the neutron production of palladium-109, however, some palladium-111 is unavoidably produced. Fortunately, this isotope also is a beta emitter and decays

through a beta-emitting isotope of silver to a stable isotope of cadmium. This material is much less hazardous than polonium-210 for several reasons.

1 It is a beta emitter and is much less of an internal hazard as the particles' energies are absorbed throughout much larger volumes.

2 It is chemically and metabolically inert and is not incorporated into the body structure except by mechanical means, such as insoluble particles being held in the nose or the lungs.

3 Since it has a short half life (14 hr), the degree of insult to tissue is reduced tremendously in a few days. Silver-111, which is always present in amounts several orders of magnitude less than palladium-109, has a larger half life (7 days) which is still much shorter than that of polonium-210.

It would appear that, because this material emits only beta particles, one could proceed with only a few centimeters of lucite for shielding. Because palladium is itself a heavy metal, however, the production of secondary electromagnetic radiation, Bremstrahlung, within the source material cannot be avoided. The amount of heavier shielding required to protect against this radiation will depend upon the geometric configuration of the source and holder, the material of the holder, and the maximum dosage levels acceptable.

The dosage rate outside the burner shown in the process of assembly in Fig. 3, due entirely to internal Bremstrahlung production, was so high as to require careful timing of necessary operations in order to prevent personnel overexposures.

Fig. 3 Assembling burner with Pd^{109}

The equipment used in this work was a Bunsen burner, with removable nozzles and head assembly. The burner was located in a vacuum chamber equipped with windows. It was the purpose of this work to study the effect of beta radiation on Bunsen flames and flames stabilized on a spherical flameholder; the sources were in the form of a thin foil and an $^1/_8$-in. palladium sphere. These were located coaxially with the nozzle and on its axis, respectively, as shown in Fig. 4. By use of this assembly, it was possible to use the foil alone in the study of Bunsen flames and to use the foil and sphere to study stabilized flames.

The assembly operation for these sources required that the foil be clamped around the head and the assembled head transferred to the burner box and clamped in place. By use of the rather elongated tools shown in Fig. 3, and by careful manipulation, it was possible to place the foil in place and secure the burner without incident. The spherical flameholder was mounted on a wire in a simple frame, which fit into a groove on the upper edge of the nozzle. It was possible to place this piece in its proper location by means of tongs 3 ft long.

Fig. 4 Pd^{109} sources in burner head

After the source was inside the burner box, its steel walls shielded much of the secondary x-radiation. The glass windows in the box presented less of a barrier to this radiation, and it was necessary that the operating personnel spend a minimum amount of time in front of the burner.

C Gold-198

Gold-198 is a beta emitter which has an associated gamma emission and decays to a stable isotope of mercury. Some gold-199 is invariably produced along with the gold-198; however, both nuclides have similar emission characteristics and almost identical half lives.

This material, which is chemically and metabolically inert and has a half life of around three days, has the same advantages regarding internal hazard as has palladium-109.

The associated gamma emission, however, provides a serious external radiation hazard which must be considered when large quantities of material are to be handled.

Fig. 5 shows schematically the shielding required for safe, convenient operation of a gold-198 transfer. Five feet of water in the tank permitted direct visual unloading, and 3 ft of sand around the tank permitted safe operation in the vicinity of the tank after the water had been removed. The tank used in this work is shown, before the installation of shielding, in Fig. 6.

It was the purpose of the study in which gold was used to ascertain the effect of beta radiation on a drag stabilized flame. Since the required data involved only the measurement of flow rates and pressures, it was possible for all operations to be conducted remotely.

The principal problem for this operation was the assembly

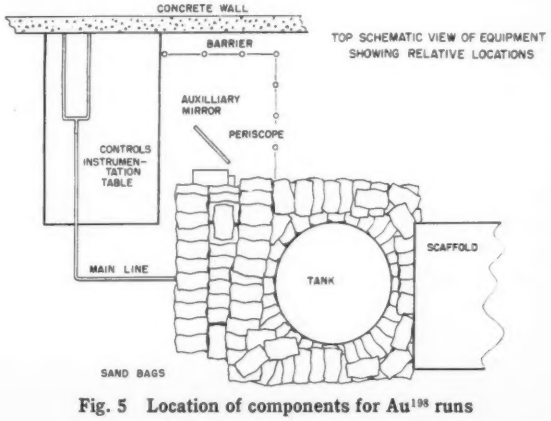

Fig. 5 Location of components for Au^{198} runs

of the burner, which is shown schematically in Fig. 7. The body of the burner and flameholder assembly were located in the bottom of the tank and the tank filled with water which served as an optically transparent shield. The source was in the form of a hollow cylinder of gold bonded to copper to increase its strength. Because of the high gamma level associated with this source, it was necessary that it be shipped in a massive lead cask and that all operations be conducted behind adequate barriers. To transfer the source, the shipping container was immersed under water, the lid removed, and the gold removed from the cask by means of long tongs. Following the removal of the cask from the water, the source was lifted by means of internal tongs to its groove in the burner wall, as shown in Fig. 8. Fig. 9 shows the gold cylinder in position. To hold the gold in place and to complete the burner assembly, the removable burner top was screwed in place by a special tool, as shown in Fig. 10. After connection of cooling lines, the burner assembly was complete. (Fig. 11 is a view of the assembled burner.)

Following this assembly, the tank lid was bolted in place and the water drained.

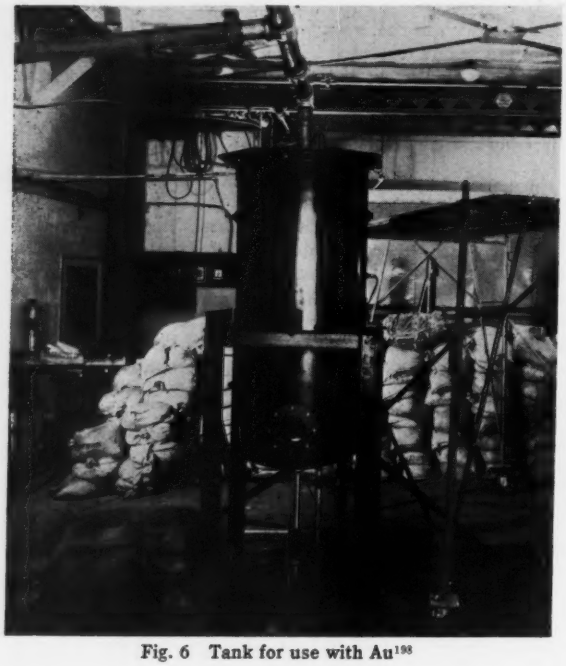

Fig. 6 Tank for use with Au^{198}

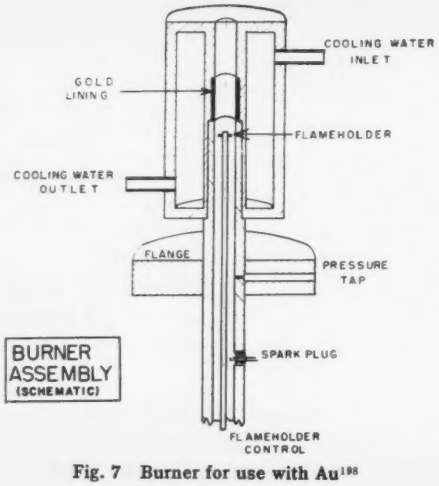

Fig. 7 Burner for use with Au^{198}

Because of the design of this equipment, it was possible to obtain data without seeing the flame. A periscope was provided for observation of the burner as an additional safeguard.

The three types of assemblies considered illustrate some of

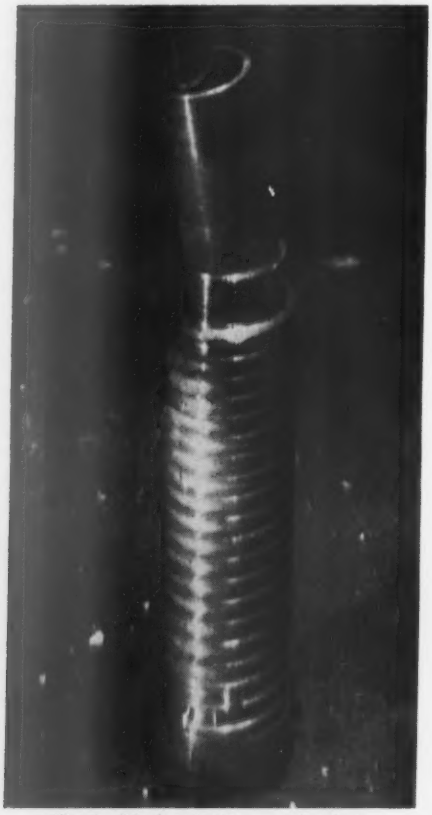

Fig. 8 Placing Au^{198} source in place

Fig. 9 Au^{198} source in place

the problems which one must face and solve. It is most important in any contemplated operation of this type that each stage in the planning and execution be done as a cooperative venture of the research worker and radiological safety personnel.

Although it has been shown experimentally that nuclear radiation may lead to improved combustion, the authors feel that is is somewhat premature to consider applications to power plants. However, the use of nuclear radiation as a tool in combustion research offers opportunities for studies in which the worker may vary at will factors which affect the kinetics of combustion, without changing the hydrodynamics of combustion, and so gain insight into the mechanism of combustion processes. The paucity of fundamental data in combustion is apparent to workers in this field and any contribution which adds to combustion science and technology should prove helpful.

The authors wish to acknowledge the financial support for this work of the University of Michigan Memorial-Phoenix Project and the U. S. Atomic Energy Commission. Alexander Weir, Jr., of the Aircraft Propulsion Laboratory, suggested some of the equipment design used in the work with Pd^{109}.

Fig. 10 Place head in place for Au^{198} operations

Fig. 11 Completed burner for Au^{198} operations

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Improved On-Off Missile Stabilization

(*Continued from page 648*)

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Improved On-Off Missile Stabilization[1]

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A new synthesis procedure for on-off control systems is presented, by means of which the delays due to time-lag and hysteresis in the system can be completely eliminated. This is readily effected by adding feedback from the on-off element itself to the conventional error and error-derivative feedbacks. By generalization (to inhomogeneous piecewise linear difference-differential equations) of the functional relationship $E(t + s) = E(t)E(s)$ (which is satisfied by any fundamental matrix of solutions of a system of homogeneous linear differential equations with constant coefficients), an explicit algorithm is developed, according to which the ideal feedback coefficients of a "perfectly" stabilized servosystem can be read off directly from the equations of the corresponding conventional system. The use of this algorithm is illustrated by application to three second order systems, and one third order system, of one degree of freedom; and to one second order system with three degrees of freedom. The results are applied to several specific relay servomechanisms and missile control systems. It is shown that hunting can be eliminated without the introduction of chattering, and that systems thus stabilized can be optimized by the addition of a switching computer, but without the necessity of dual mode control. It is assumed without proof that once the delays are eliminated, the resultant "ideal" system will be stable. In the examples given, this is known to be true, but the standard proofs are rather laborious.[3]

Introduction

THE simple "on-off" or relay type of control system has frequently been employed for missile stabilization in place of the better understood but more cumbersome and delicate continuous "linear" servosystem. For example, Flügge-Lotz (9)[4] has studied the effects of discontinuous (flip-flop) aileron or horizontal tailplane control in an aerodynamic missile; and Felt (8) has analyzed a relay actuated jet reaction control system for a ballistic missile (the Viking rocket after burnout). More recently, jet reaction controls have been applied to vertical take-off (VTO) aircraft. But the improvement of such systems has been retarded by mathematical difficulties arising in their analysis.

In the first place, the mechanics of the system, which is piecewise linear, is nonlinear in the large. Moreover, the nonlinearity is essential; by this we mean that it is not possible, as with conventional continuous control systems, to invoke the theories of Poincaré and Lyapunov (3, 7, 11) in justification (4, 6) of design by use of the standard linear stability criteria of Routh, Hurwitz, and Nyquist (10, 15).

In the second place, the high velocities attainable by the controlled missile demand that the analysis include the effects of time lags and delays in the system (cf. 6). Indeed, the effect of these delays is critical: witness the steady-state "hunting" with which the systems mentioned above are afflicted (8, 9).

In a schematic diagram, it is convenient to locate all time delays and hysteresis in the relay or on-off element; however, these delays can actually be located anywhere in the system without changing the analysis. For example, in a jet reaction control system the delay in the thrust buildup of the rocket motor is most significant; if, as a first approximation, it is considered constant, it can be added to the relay time delay.

In reflection of these assumptions, the system must be described mathematically not by ordinary differential equations but rather by difference-differential equations. As is well known to those interested in combustion instability in rocket motors (14), *linear* difference-differential equations with constant coefficients are fairly tractable (10, 6, 6 bis); it is even possible to cope with the accompanying transcendental transfer functions by means of a modified Nyquist diagram (15, Chap. 8). But in spite of a considerable literature devoted to it (cf. 6), the subject of *nonlinear* difference-differential equations has not attained maturity. Indeed, concerning a subject of prime importance in control analysis, Bellman (4) says: "In the direction of periodic solutions of [these] equations, very little has been done beyond the application of the heuristic techniques[5] that have been so successful in the theory of ordinary differential equations."

Finally, even if these analytical difficulties are overcome in special cases (cf. 1), the analysis usually reveals that no physically feasible values of the system parameters will produce entirely satisfactory performance. Hence, recourse must be had to "compensating" or stabilizing networks or devices. But no general theory of the synthesis of such devices has been available.

Most frequently, compensation is effected by employment of linear (or, occasionally, quadratic) error rate feedback in addition to the standard error feedback. For example, Flügge-Lotz (9, p. 127) advocates rate gyro feedback, while Felt (8) employs a linear resistance reactance phase lead or "differentiating" network, which simulates linear error rate or tachometer feedback. But this "anticipatory network" type of compensation (cf. 13) introduces its own difficulties. Either one must employ moderate compensation, and accept, as does Felt, a periodic motion as the steady state of the system; or one must employ the more drastic method of Flügge-Lotz in which the parameters are deliberately chosen so as to lead to "after end-point motion." This phenomenon, called "chattering" by servo engineers, is undesirable in relay servosystems of the type of (8, 16) because it causes the relay to wear out more quickly.

Nor is stabilization without chattering superfluous in, e.g., research rockets during coasting flight, for the instruments carried measure cosmic rays, solar radiation, and other phenomena with directional properties.

The principal object of this paper is to present a new general theory of the synthesis of on-off servosystems, rendered stati-

[1] This work was performed under Office of Naval Research Contract N6ori-105, Task Order V, Project NR043-942. It includes a partial summary of other contract research; cf. Ref. (1).

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Presented at the IAS 24th Annual Meeting Joint Session with ARS, New York, N. Y., Jan. 24, 1956.

[3] A note presenting a very general and rapid new technique for choosing stable ideal on-off systems of any order has been submitted to this JOURNAL by the author.

[4] Numbers in parentheses indicate References at end of paper.

[5] It is proved in (1) that these techniques are sometimes legitimate; cf. also (2 bis).

cally stable by a true "predictor network" which involves none of the side effects (e.g., chattering) of the conventional anticipatory networks; in fact, this network completely eliminates the delays from the system (for step inputs and often for ramp inputs as well). This stabilization is accomplished in a practical manner, by combining the conventional (linear) error and error rate feedbacks with (nonlinear) feedback from the on-off control element itself. The ideal ratios of the error rate and relay feedbacks to the error feedback—i.e., the compensator parameters—can be read off from the differential equations (as explicit functions of the remaining, fixed, system parameters) according to a recent algorithm of the author (1, 2).

Since the predictor and the delays all but cancel each other from the difference-differential equations, the transient behavior of the combined system can be found readily by analysis of the corresponding uncompensated but "ideal" (i.e., undelayed) system. (Cf. the survey of the ideal analyses of Flügge-Lotz, Bushaw, and Rose given in (15 and 1).) In fact, for a properly chosen system it will be clear a priori that the corresponding ideal system admits of no limit cycles: without delays, there will be no energy storage to offset the dissipation of energy by friction, and so no self-sustained oscillations. The mathematical abstraction of this technique is called "Lyapunov's second method."[3]

The precise meaning of these remarks will first be clarified by detailed consideration of a specific example involving one degree of freedom (the standard relay servomechanism). We shall then state our algorithm and illustrate its use by application to three other systems with one degree of freedom: the second order systems of Felt (8) and Flügge-Lotz (9, Chaps. 1–7), and a certain third order system.

In conclusion, we mention a second order system of three degrees of freedom (9, Chap. 8). For such a complex system, it may not be feasible to use the full ratios of all feedbacks necessary for a true predictor network; for example, no error derivatives higher than second can be used because of "noise." Moreover, it is not immediately clear in what sense (i.e., algebraic sign) the various feasible feedbacks should be taken in order to produce even an anticipating effect. But it will be seen that this information, also, can be obtained directly from the basic algorithm. It seems intuitively clear that if the coefficients are chosen in this manner, the corresponding ideal system will be stable.[6]

The Relay Servomechanism

Consider the system schematically represented in Fig. 1. The error $e(t) = r(t) - c(t)$ is the difference between the reference variable or input to the system $r(t)$ and the controlled variable or system output $c(t)$. The relay is a three state contactor ($F = -1, 0, +1$) having a dead zone of width $2\bar{e}$, a hysteresis effect (difference between drop out and pull in current) of magnitude $2\Delta\bar{e}$, and a constant time delay of t_d sec. The difference-differential equation which describes

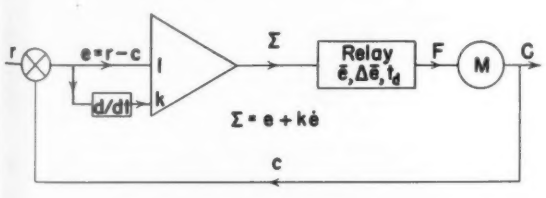

Fig. 1 Typical compensated servo

this system for a step input $r = \text{const}$ is (Weiss (16))

$$\ddot{e}(t) + \dot{e}(t) + F(\Sigma(t - t_d)) = 0 \quad \ldots\ldots [1]$$

$$\Sigma(t) \equiv e(t) + k\dot{e}(t) \quad \ldots\ldots [2]$$

where (see Fig. 2)

$$F(\Sigma(t)) = \begin{cases} 0, \ -\bar{e} + (\operatorname{sgn} \dot{\Sigma}(t))\Delta\bar{e} < \Sigma(t) < \bar{e} + (\operatorname{sgn} \dot{\Sigma}(t))\Delta\bar{e} \\ \operatorname{sgn} \Sigma(t), \text{ otherwise}^7 \end{cases} \quad \ldots [3]$$

(Here e and t are dimensionless coordinates which can be obtained by a change of scale (16).) The system [1]–[3] thus contains four dimensionless parameters, $\bar{e}$, $\Delta\bar{e}$, t_d, and k, which are subject to the inequalities (1)

$$\begin{matrix} 0 \le 2\bar{e} \le 1 & 0 \le 2\Delta\bar{e} \le 1 \\ 0 \le t_d \le 1 & 0 \le k < \infty \end{matrix} \quad \ldots\ldots [4]$$

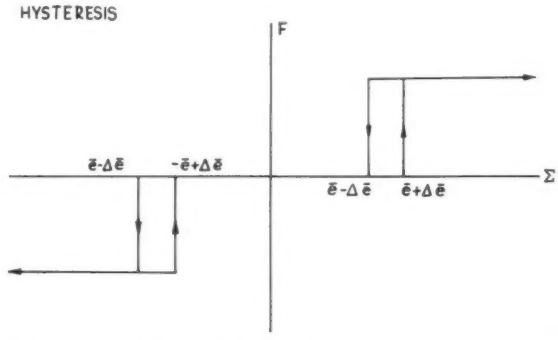

Fig. 2 Characteristic of relay with dead zone and hysteresis

The transient response of [1] is illustrated in Fig. 3.

In the uncompensated case $k = 0$ this system encompasses three mutually exclusive possibilities: it either (i) behaves like an underdamped linear oscillator, $e(t)$ coming to rest ($\dot{e} = \ddot{e} = 0$) with $0 \le |e(t)| \le 2\bar{e}$ after a finite number of oscillations; or (ii) possesses a single stable limit cycle, i.e., a "soft" self-sustained oscillation; or (iii) possesses one unstable and one stable limit cycle, the stable one being the larger, i.e., a "hard" self-sustained oscillation.

These facts were proved in (1), as well as a complete analysis of the bifurcation of the periodic solutions of [1] as the relay parameters vary in the domain [4]. The final result is as follows. Let

$$\left.\begin{aligned} \Delta\bar{e}^*(\bar{e}) &= {}^1/_2[\,|\log(1 - 2\bar{e})| - 2\bar{e}\,] \\ t_d^* &= t_d + (e^{t_d} - 1)/(2e^{t_d} - 1) \\ \sigma &= (e^{t_d} - 1 - t_d) - 2\Delta\bar{e} \\ \delta &= \sigma_3 + \log \sigma_4 \end{aligned}\right\} \quad \ldots\ldots [5]$$

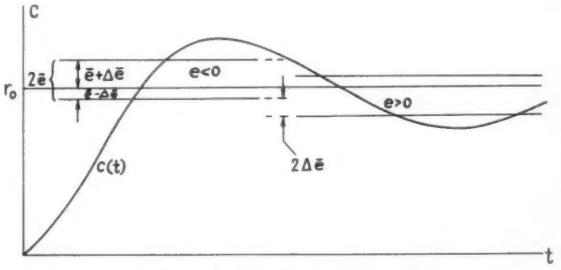

Fig. 3 Transient response of Equation [1]

[6] A rigorous, but slightly less straightforward method for assuring stability is presented in the note submitted to this JOURNAL. It is based on a mathematical technique which is known for its power and generality. Several of the systems discussed will also be analyzed by the method.

[7] As pointed out by John Bertram, this concise definition of $F(\Sigma)$ is not strictly correct unless F is changing in the sequence $F = -1, 0, +1; -1, 0, +1; \ldots$. For "chattering" ($F = -1, 0; -1, 0; \ldots$) additional inequalities are needed. A discussion of the errors in the model of Fig. 2 is given in S. K. Chao, AIEE Paper 56-456, to appear in *AIEE Trans.*

where

$$\sigma_1 = e^{t_d} - 1 + t_d - 2\bar{e} \qquad \sigma_2 = e^{t_d} + 1 + t_d - 2\bar{e} \ldots [6]$$

$$\sigma_3 = \sqrt{\sigma_1(\sigma_1 + 2)} \qquad \sigma_4 = (\sigma_2 - \sigma_3)/(\sigma_2 + \sigma_3) \ldots . [7]$$

Then the tables in Fig. 7 hold.

Fig. 7 shows it is frequently impractical to make $\Delta\bar{e}$ and t_d so small in relation to $\bar{e}$ that the desired type of performance (case (i)) is attained. Of course, static stability could always be obtained by increasing $\bar{e}$, but this would result in impermissibly large static errors.

Consequently one must usually employ $k > 0$. For purposes of comparison, let us also consider the quadratic error rate feedback scheme in which (2) is replaced by

$$\Sigma_1(t) = e(t) + \kappa |\dot{e}(t)| \dot{e}(t) \ldots \ldots \ldots \ldots [8]$$

To the possibilities mentioned above, we must now (when $k > 0$ or $\kappa > 0$) add: (iv) The system behaves (roughly) like an overdamped linear oscillator: after a few oscillations it "chatters" along the locus $\Sigma = 0$ or $\Sigma_1 = 0$ in the $(e, \dot{e})$-plane until $e(t)$ comes to rest as in case (i).

Let

$$s = [1 - \exp(-2[\bar{e} + \Delta\bar{e}])]^{-1} \ldots \ldots \ldots [9]$$

$$k_{\min} = [1 - s(2\bar{e} - (e^{-t_d} - 1 + t_d))][(1 - s(1 - e^{-t_d}))]^{-1} \quad [10]$$

let $k_{\max}$ be given by the solution of

$$k_{\max} + \log(e^{-t_d} + t_d + 2\Delta\bar{e} - e^{-t_d} k_{\max}) = 0 \ldots . [11]$$

and let

$$k_{(i)} = \min(1 - 2\bar{e}, k_{\max}) \ldots \ldots \ldots \ldots [12]$$

Then it can be proved (1) that for [2] we have (see Fig. 4)

$$\left.\begin{array}{ll} k_{\min} \leq k \leq k_{(i)} & \text{Case (i)} \\ k_{\max} < k < \infty & \text{Case (iv)} \end{array}\right\} \ldots \ldots \ldots [13]$$

Similarly, for [8] we have: When $t_d = 0$ and

$$s[1 - s(2\bar{e})] \leq \kappa < 1 - 2\bar{e} \ldots \ldots \ldots \ldots [14]$$

case (i) occurs; but neither the maximum value of κ which can be employed without introducing chattering, nor results for $t_d > 0$ have been obtained.

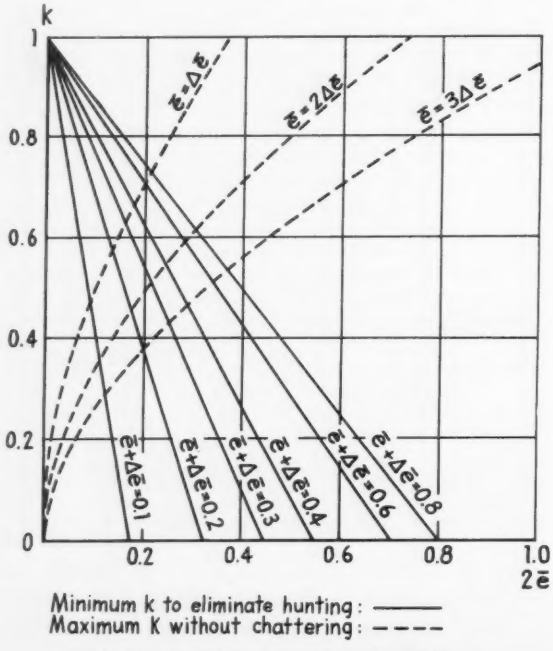

Fig. 4 Conventional error rate stabilization

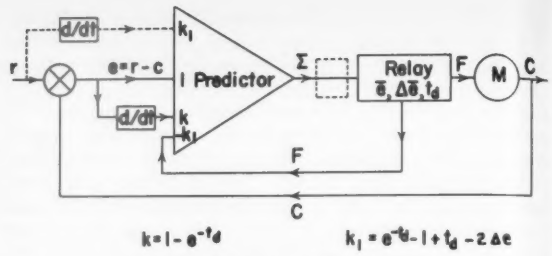

Fig. 5 Perfectly stabilized servo

Now suppose that it is not feasible to use $k < k_{(i)}$ (e.g., suppose $k_{(i)} < k_{\min}$) and yet case (i) is desired. It is shown in (1) that this can be accomplished by introducing relay feedback as in Fig. 5.

In other words, replace [2] by

$$\Sigma_2(t) = e(t) + k\dot{e}(t) - k_1 F(\Sigma_2(t - t_d)) \ldots \ldots [15]$$

According to algorithm (A) which is explained below, if one lets

$$k = 1 - e^{-t_d} (> 0) \ldots \ldots \ldots \ldots [16]$$

$$k_1 = e^{-t_d} - 1 + t_d (> 0) \ldots \ldots \ldots [17]$$

then

$$\Sigma_2(t) = e(t + t_d) \ldots \ldots \ldots \ldots [18]$$

But then $\Sigma_2(t - t_d) = e(t)$, so that the system of Fig. 5 is equivalent to that of Fig. 1 in which one puts $k = t_d = 0$. Finally, if [17] is replaced by

$$k_1 = (e^{-t_d} - 1 + t_d) - 2\Delta\bar{e} \ldots \ldots \ldots [19]$$

then, according to algorithm (B) below, the system of Fig. 5 is equivalent to the ideal system of Fig. 6 ($k = t_d = \Delta\bar{e} = 0$).

The dotted box in Fig. 5 represents the proper location for an additional compensating or optimizing (cf. 12, 1) network. (Further details concerning optimization will be found in (2 bis).) Such a network would have the same effect as if it were located in the same position in Fig. 6.

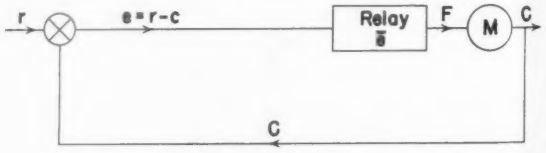

Fig. 6 Ideal servo

For example, suppose a phase lead network is added which has the effect of replacing $\Sigma_2(t)$ by

$$\Sigma_3(t) = \Sigma_2(t) + k\dot{\Sigma}_2(t) \ldots \ldots \ldots \ldots [20]$$

Then the system [1]–[3] *with* Σ *of* [2] *replaced by* Σ_3 *of* [20] *will behave the same as the system* [1]–[3] *of Fig. 1 with* $\Delta\bar{e} = t_d = 0$ *and* $k > 0$. The k in [20] is of course not the same as that in [16]; indeed, from [15], [16], and [19]

$$\Sigma_3(t) = e(t) + k^1\dot{e}(t) - k_1{}^1 F(\Sigma_3(t - t_d)) \ldots \ldots [21]$$

where

$$k^1 = (e^{-t_d})k + (1 - e^{-t_d}) \ldots \ldots \ldots \ldots [22]$$

$$k_1{}^1 = (1 - e^{-t_d})k + (e^{-t_d} - 1 + t_d) - 2\Delta\bar{e} \ldots . [23]$$

From [21] it is obvious that the feedback [20] can be accomplished *directly* as in [15], by merely replacing k, k_1 of [16], [19] by k^1, $k_1{}^1$ of [22], [23].

In the case of a ramp input

$$r(t) = \Omega t + \text{const}$$

$F(\Sigma)$ of [1] is replaced by $F(\Sigma) - \Omega$. Hence Σ_3 of [21] must be replaced by

$$\Sigma_3^1(t) = k_{11}\dot{r}(t) + e(t) + k^1\dot{e}(t) - k_1^1 F(\Sigma_3^1(t - t_d)) \ldots [24]$$

Here $k_{11} = k_1^1 + 2\Delta\bar{e}$. In the case $\dot{r}(t) = \Omega = \text{const}$, the italicized result above, which is based on [18], continues to hold. This suggests that for fairly slowly varying dynamic inputs, in which $\dot{r}(t)$ ($<<1$) is not constant, the relation [18] holds to a high degree of approximation (for use Taylor series as in Minorsky (13)). Thus (1) for "admissible" dynamic inputs to a relay servo the rate of change of the reference variable should itself be employed as a secondary reference variable (cf. dotted path in Fig. 5).

The Prediction Algorithm

The result [15]–[18] is based on the following *prediction algorithm* (1, 2). Consider the difference-differential equation

$$\dot{e} = Ae + f(\Sigma_0(t - t_d))$$

where e is a (real) n-vector, A is a constant $n \times n$ matrix, and $f = F\gamma$, where γ is a constant vector and F is given by [3]; $\Sigma_0(t)$ is a scalar linear function of e which is so chosen that the corresponding "ideal" system $\dot{e} = Ae + f(\Sigma_0(t))$ would give the desired type of performance. One wishes to replace $\Sigma_0(t)$ by $\Sigma(t)$, which is to depend linearly on e and also on f and which is to have the property that

$$\Sigma(t - t_d) = \Sigma_0(t)$$

(A) Write the transient response of the system (for f considered constant) as a set of linear forms in the initial conditions and f. (This can be done easily by use of the Laplace transform.) Put $t = t_d$. Then the ideal feedback coefficient of each of the quantities (including f) is given by the coefficient of the initial value of that quantity.

(B) In order to remove hysteresis also, add $2\Delta\bar{e}$ to the coefficient for f obtained from (A).

These results depend on the hypothesis that in certain time intervals f is constant for at least $2t_d$ sec. This hypothesis is usually met in practice; for example, in the relay servo considered above, the hypothesis is met if $t_d < \bar{e}$. More details concerning (A) and (B) are given in (1) and (2).

The Jet Reaction Control System

The only schematic difference between this system (8) and the relay servo just considered is that the viscous friction term of [1] is missing

$$\ddot{e}(t) + F(\Sigma(t - t_d)) = 0 \ldots [25]$$

where Σ and F are given by [2] and [3]. Instead of using [18], and then adding a second network to obtain [20], we can proceed directly to that end in one step as in [21]–[23]. In fact, from [25] it is immediate that

$$e(t) = e_0 + \dot{e}_0 t - (t^2/2)F$$

$$\dot{e}(t) = \dot{e}_0 - tF$$

Hence, according to (A)

$$e(t + t_d) = e(t) + t_d\dot{e}(t) - (t_d^2/2)F(\Sigma(t - t_d))$$

$$\dot{e}(t + t_d) = \dot{e}(t) - t_d F(\Sigma(t - t_d))$$

Thus, let $\Sigma(t - t_d)$ in [25] be given by

$$\Sigma(t) = e(t + t_d) + k\dot{e}(t + t_d) + 2\Delta\bar{e}F(\Sigma(t - t_d)) = e(t) + (k + t_d)\dot{e}(t) - [t_d k + (t_d^2/2) - 2\Delta\bar{e}]F \ldots [26]$$

Then the delays in F are cancelled. Equation [26] says: If M in Fig. 5 represents missile dynamics (after burnout)

TABLE 1	$t_d < 2\bar{e} < t_d^*$	
$\Delta\bar{e} < \Delta\bar{e}^*(\bar{e} - t_d/2)$	$\delta < \sigma$	No oscillations
	$0 < \sigma < \delta$	Hard oscillations
$\Delta\bar{e} > \Delta\bar{e}^*(\bar{e} - t_d/2)$		Soft oscillations

TABLE 2	$t_d^* < 2\bar{e} \leq 1$	
$\Delta\bar{e} < \Delta\bar{e}^*(\bar{e} - t_d/2)$		No oscillations
$\Delta\bar{e} > \Delta\bar{e}^*(\bar{e} - t_d/2)$		Soft oscillations

Fig. 7 Behavior of ideal servo

rather than those of a servomotor, replace k and k_1 in the predictor of Fig. 5 and [15] with

$$k^1 = k + t_d \ldots [27]$$

$$k_1^1 = t_d k + (t_d^2/2) - 2\Delta\bar{e} \ldots [28]$$

and the system will behave like that of Fig. 1, [1]–[3], with $\Delta\bar{e} = t_d = 0$.

Notice that since the term $\dot{e}(t)$ is missing from [25], there is no difference between ramp and step inputs to this system. Hence, to a first approximation, [27] and [28] can be used when [25] is subject to a slowly varying dynamic input.

An Aerodynamic Control System

In the case of position control (9, Eq. [48]) we have

$$\ddot{e}(t) + \dot{e}(t) + f \cdot e(t) + F(\Sigma(t - t_d)) = 0 \ldots [29]$$

This system is distinguished from the relay servo by the presence of natural linear restoring forces ($f > 0$). By application of the Laplace transform (10, 15) one finds that the solution of [29] is

$$e(t) = e^{-t/2}(2\cos vt + v^{-1}\sin vt)e_0 + 2v^{-1}e^{-t/2}(\sin vt)\dot{e}_0 + [(1/4) + v^2]^{-1}[e^{-t/2}(2\cos vt + v^{-1}\sin vt) - 1]F \ldots [30]$$

where

$$v = [f - (1/4)]^{1/2} \ldots [31]$$

and where it is assumed that $v > 0$. (The result for $f < 1/4$ can be obtained in terms of the hyperbolic functions by a well-known transformation.) From [30]

$$\dot{e}(t) = e^{-t/2}[(2v)^{-1} - 2v](\sin vt)e_0 + e^{-t/2}[2\cos vt - v^{-1}\sin vt]\dot{e}_0 \ldots [32]$$

Then according to (A)

$$e(t + t_d) = e^{-t_d/2}(2\cos vt_d + v^{-1}\sin vt_d)e(t) + 2v^{-1}e^{-td/2}(\sin vt_d)\dot{e}(t) + [(1/4) + v^2]^{-1}e^{-td/2} \times (2\cos vt_d + v^{-1}\sin vt_d)F \ldots [33]$$

$$\dot{e}(t + t_d) = e^{-td/2}[(2v)^{-1} - 2v](\sin vt_d)e(t) + e^{-td/2}[2\cos vt_d - v^{-1}\sin vt_d]\dot{e}(t) \ldots [34]$$

Hence in order to have

$$\Sigma(t - t_d) = e(t) + k\dot{e}(t) \quad \ldots\ldots [35]$$

in [29], one should by [33], [34], and (B) use

$$\Sigma(t) = c_0 \cdot e(t) + c_1 \cdot \dot{e}(t) + c_2 \cdot F(\Sigma(t - t_d)) \quad \ldots\ldots [36]$$

with

$$c_0 = \{k[(2v)^{-1} - 2v] \sin vt_d + 2\cos vt_d + v^{-1} \sin vt_d\} e^{-t_d/2} \quad [37]$$

$$c_1 = \{k[2\cos vt_d - v^{-1} \sin vt_d] + 2v^{-1} \sin vt_d\} e^{-t_d/2} \quad \ldots\ldots [38]$$

$$c_2 = e^{-t_d/2}\,[(1/4) + v^2]^{-1}(2\cos vt_d + v^{-1} \sin vt_d) + 2\Delta\bar{e} \quad \ldots [39]$$

In this case the ramp input cannot be treated, owing to the term $f \cdot e(t)$ which would introduce a term $f \cdot \Omega t$ into [29].

A Third Order System

By a change of scale (1) the relay servo with non-negligible motor armature inductance becomes

$$\dddot{e}(t) + \ddot{e}(t) + A\dot{e}(t) + F(\Sigma(t - t_d)) = 0,\ A > 0 \quad \ldots [40]$$

Here the solution $e(t)$ is equal to the right-hand side of [30] plus the terms

$$e_0 + A^{-1}(\dot{e}_0 + \ddot{e}_0) + A^{-1}(A^{-1} - t)F(\Sigma(t - t_d))$$

Accordingly, it is readily found that in order to have [35] in [40] use

$$\Sigma(t) = d_0 \cdot e(t) + d_1 \cdot \dot{e}(t) + d_2 \cdot \ddot{e}(t) + d_3 \cdot F(\Sigma(t - t_d)) \quad \ldots [41]$$

with

$$d_0 = c_0 + 1 \qquad d_1 = c_1 + A^{-1}$$

$$d_2 = A^{-1} \qquad d_3 = c_2 + A^{-2} - A^{-1}(k + t_d)$$

where c_0, c_1, c_2 are as in [37]–[39].

In this case it is possible to compensate for a ramp input by adding a term $-d_3 \cdot \dot{r}(t)$ to the right-hand side of [41].

As an exercise in the use of (A), (B) the reader might at this point verify the results [15]–[25], which were stated without proof.

A System With Three Degrees of Freedom

In discussing the longitudinal motion of a missile with discontinuous position control, Flügge-Lotz (9) derives the system of equations

$$a_{10}\alpha + b_{10}\theta + c_{10}v + c_{11}\dot{v} = 0$$

$$a_{20}\alpha + a_{21}\dot{\alpha} + b_{20}\theta + b_{21}\dot{\theta} + c_{20}v - A \cdot F = 0$$

$$a_{30}\alpha + a_{31}\dot{\alpha} + b_{31}\dot{\theta} + b_{32}\ddot{\theta} + T \cdot F = 0 \quad \ldots\ldots [42]$$

here α, θ, v are the deviations from their values in a straight flight path of the angle of attack of the wing, of the angle of the missile with a horizontal plane, and of the missile velocity. (The relation of the a_{ik}, b_{ik}, c_{ik} to the missile characteristics is given by correlating equations [164] and [165] of (9) by means of Appendix I of (9); in [42] we have replaced c_{10}, c_{11}, and c_{20} of (9) by Vc_{10}, Vc_{11}, and Vc_{20}.) In [42], F is given by [3], and

$$\Sigma(t) = \theta(t) + k\dot{\theta}(t) \quad \ldots\ldots [43]$$

Feedback of θ only is employed since θ is more convenient to record than α or v. For aileron control, $A = +1$, $T = 0$; for horizontal tailplane control, $A = 0$, $T = +1$.

In order for the uncontrolled system to be stable, a certain fourth degree polynomial (Eq. [167] of (9)), whose coefficients are polynomials in the a_{ik}, b_{ik}, c_{ik}, must have only roots with negative real parts. Once the four roots of this polynomial are determined, the explicit solution of [42] as a set of linear forms in the initial conditions

$$\alpha_0,\ \theta_0,\ \dot{\theta}_0,\ v_0 \quad \ldots\ldots [44]$$

can be obtained by expanding the twelve fourth order determinants in equations [172a]–[172c] of (9) and evaluating the coefficients of F from the appropriate column of Table IX of (9). (For [44], (9) uses α_{i_m}, θ_{i_m}, etc.)

In this way one obtains, from (A) that

$$g_i(t + t_d) = l_i\alpha(t) + m_{i1}\theta(t) + m_{i2}\dot{\theta}(t) + n_iv(t) + K_iF(\Sigma(t - t_d)) \quad \ldots\ldots [45]$$

($i = 1, 2, 3$), where $g_1 = \alpha$, $g_2 = \theta$, and $g_3 = v$, and where l_i, m_{ik}, n_i, K_i are functions of t_d, A, T, and a_{ik}, b_{ik}, c_{ik}.

Now Flügge-Lotz shows, by a detailed discussion (9, pp. 130–159), that for successful damping of disturbances one should choose $A = +1$, $T = 0$ in [42] and a small *positive* value of k in [43].[3, 6]

A very short approach to the extension of such results can be based on (A). By differentiating Eq. [172b] of (9) before applying (A), one obtains, in addition to [45] for $i = 2$

$$\dot{\theta}(t + t_d) = l_2{}^1\alpha(t) + m_2{}^1\theta(t) + m_{22}{}^1\dot{\theta}(t) + n_2{}^1v(t) \quad \ldots [45\text{ bis}]$$

Now in order to effectively employ [43], one should replace $\theta(t)$, $\dot{\theta}(t)$ on the right-hand side of [43] by $\theta(t + t_d)$, $\dot{\theta}(t + t_d)$; i.e., from [45], [45 bis] one should let

$$\Sigma(t) = p_1\alpha(t) + p_2\theta(t) + p_3\dot{\theta}(t) + p_4v(t) + p_5F(\Sigma(t - t_d)) \quad \ldots [46]$$

where

$$p_1 = l_2 + kl_2{}^1 \qquad p_2 = m_{21} + km_{21}{}^1 \quad \ldots\ldots [47a]$$

$$p_3 = m_{22} + km_{22}{}^1 \qquad p_4 = n_2 + kn_2{}^1 \quad \ldots\ldots [47b]$$

$$p_5 = K_2 \quad \ldots\ldots [47c]$$

This indicates that if it is desired to replace [43] by a multiple feedback control [46], with p_k replaced by $p_k{}^1$ ($k = 1, \ldots, 5$) and involving one or more of $p_2{}^1$, $p_4{}^1$, or $p_5{}^1$ not equal to zero, one should (at least) let $p_k{}^1$ have the same sign as the corresponding ideal value of p_k ($k = 1, \ldots, 5$) given by [47].

Summary

It is first necessary to choose an on-off control system which would be stable if no delays were present.[3] The next step is to compensate for the delays which are actually present, by means of algorithms (A) and (B). For systems with several degrees of freedom it may be preferable to use the predictor algorithm only in part, that is, to design an anticipatory stabilizer. However, for many typical missile and aircraft control systems it appears feasible and often desirable to effect full stabilization by means of the predictor network. And, finally, if a very high performance servosystem is desired, the author would recommend an on-off control system which is first stabilized by a predictor network and to which an optimizing switching device (2 bis) is then added. Such a device should be added in the position of the dotted box shown in Fig. 5.

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(*Continued on page 643*)

Application of Hydraulic Analog Method to One-Dimensional Transient Heat Flow[1]

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The analogy between one-dimensional transient heat flow and the flow of a liquid through a tube with axially distributed capacitors is reviewed. This analogy is extended to include certain boundary conditions which occur in problems involving aerodynamic heating. The design and construction of a hydraulic analog computer are described. Operation of this equipment demonstrated (a) that nonlinear variations of environmental temperature and heat transfer coefficient with time, and nonlinear variations of thermal properties of a wall material with temperature can be handled easily, and (b) that a clear physical picture of the temperature variations in the wall with space and time is obtained by observing the computer during its operation. Analog results are given for 1/4- and 1/2-in.-thick skins subjected to aerodynamic heating which varies nonlinearly with time.

Nomenclature

A = cross-sectional area of capillary tube
$\bar{A}$ = cross-sectional area of capacitor
c = heat capacity
d = diameter of capillary tube
g = acceleration of gravity
h = heat transfer coefficient
H = hydraulic head (including momentum of liquid)
k = thermal conductivity
q = heat flow per unit area and per unit time
Q = volume flow per unit time
s = one half of the plate thickness in sample problem
t = time
T = temperature
x = distance measured in the flow direction
α = thermal diffusivity
β = mechanical property analogous to thermal diffusivity
η = scale factor
ν = kinematic viscosity
ρ = density
$\phi = \int_{T_0}^{T} \frac{k}{k_0}\, dT$

Subscripts

bl = boundary layer
f = fluid flow
h = heat flow
0 = reference temperature (0 F)
r = recovery
t = time
w = interface between wall and gas stream
x = length

Presented at the ARS Fall Meeting, September 18–21, 1955, Los Angeles, Calif.

[1] This paper is based on work carried out under Army Ordnance Contract DA-04-495-ORD-478.

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[4] Numbers in parentheses indicate References at end of paper.

1 Introduction

AN EFFICIENT design of certain structures which are subjected to transient heating is achieved if the strucures are light in weight and are, at the same time, strong enough to withstand the loads imposed upon them. In order to design efficiently for such requirements, one must have available the information (e. g., temperature distributions in the structures) needed to calculate thermal stresses and structural residual strengths occurring during the heating period. Temperature distributions in such structures can be obtained analytically and graphically provided that the problem is not complicated by complex geometries, by boundary conditions which vary with time, and by thermal properties which vary with temperature. However, if the problem contains one or more of these complications, then practical solutions are difficult to obtain using conventional solution methods. Consequently, as a first step in the development of a solution method for the more complicated problems, a method was sought which would facilitate determining quickly and inexpensively the one-dimensional transient heating of a flat plate which is subjected to boundary conditions varying with time and which has thermal properties varying with temperature.

Two analogies were considered as possible solution methods: the electric analogy and the hydraulic analogy. The electric analogy was considered first because of the popularity which electric analog computers enjoy today. Although these computers were found to be available for this type of work, it was learned also that the cost of equipment which would simulate variations of thermal properties with temperature and variations of boundary conditions with time was high. Furthermore, it became apparent that with the hydraulic analog computer one could (a) simulate variations of thermal properties with temperature by using equipment which could be fabricated easily, and (b) simulate easily variations of boundary conditions with time by using equipment which could be operated manually. (Hydraulic analog computers can be built which have time constants much greater than the time constants for electric analog computers.) As a result, the development of a hydraulic analog computer was initiated.

The hydraulic analog was used first for the study of transient heat transfer by A. D. Moore (1)[4] of the University of Michigan in 1933–1935. He encountered construction and operation difficulties because capillary tubing with uniform cross-sectional areas was difficult to obtain at that time. In 1948, C. S. Leopold (2) reported on the construction and use of the hydraulic analog for the solution of thermal storage, radiation, convection, and conduction problems. He improved Moore's unit by using a high-viscosity silicone liquid, permitting thereby the use of tubes with relatively large diameter. M. B. Coyle (3) described in 1951 an improved unit which simulated variations with temperature of the thermal properties of the material. In the work described in the present paper, this hydraulic analog computer was modified to include provisions for simulating heat transfer

coefficients and environmental temperatures which vary with time. Techniques for simulating radiation and surface fusion are suggested.

2 An Analogy Between Heat Flow and Fluid Flow

The analogy between one-dimensional transient heat flow and a certain type of fluid flow (upon which analogy the design of the hydraulic analog computer was based) will be shown theoretically by writing in finite difference form the equations which describe these two flows and by calling attention to the similarity between these two equations. The analogy will be extended then to include certain boundary conditions which occur in problems involving aerodynamic heating.

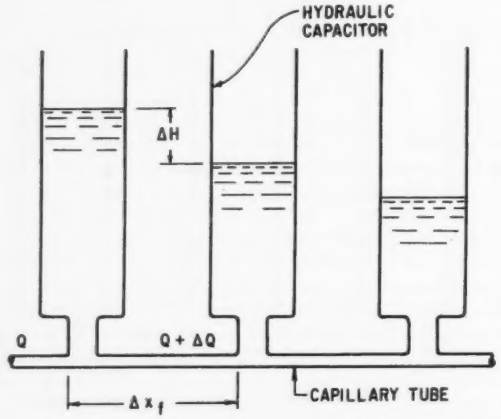

Fig. 1 Sketch of the hydraulic system which is compared with one-dimensional heat transfer system

Consider laminar flow of a liquid in a horizontal capillary tube which has constant cross-sectional area (Fig. 1). Assume hydraulic capacitors (vertical towers) to be connected at regular intervals to this tube. Equating the forces acting on the liquid to the momentum change of the liquid, one obtains the momentum conservation equation

$$Q = -\frac{A^2 g}{8\pi\nu}\frac{\Delta H}{\Delta x_f} \quad [1]$$

Here Q is volume flow per unit time; A is cross-sectional area of the capillary tube; g is acceleration of gravity; ν is kinematic viscosity; H is hydraulic head (including the momentum of the liquid); x is distance between adjacent hydraulic capacitors; and the subscript f refers to fluid flow. (Note that the momentum of the liquid is altered when liquid is added to or subtracted from the stream at the capacitor locations; it has been assumed implicitly that at each capacitor location the liquid momentum is converted without loss of head into pressure, and vice versa.) Equating the rate at which liquid is bled from the capillary tube to the rate at which liquid is being added to the capacitors, one obtains the volume conservation equation

$$\frac{\Delta Q}{\Delta x_f} = -\frac{\bar{A}}{\Delta x_f}\frac{\Delta H}{\Delta t_f} \quad [2]$$

Here t is time, and $\bar{A}$ is the cross-sectional area (varying perhaps with vertical distance) of a capacitor. Differentiating Equation [1] with respect to distance and equating then the right side of differentiated Equation [1] to the right side of Equation [2], one obtains

$$\frac{A^2 g}{8\pi\nu}\frac{\Delta^2 H}{\Delta x_f^2} = \frac{\bar{A}}{\Delta x_f}\frac{\Delta H}{\Delta t_f} \quad [3]$$

Equation [3] describes laminar flow of a liquid through a capillary tube with axially distributed hydraulic capacitors.

The equation for one-dimensional transient heat flow can be written in the finite difference form

$$\frac{\Delta}{\Delta x_h}\left(k\frac{\Delta T}{\Delta x_h}\right) = \rho c\frac{\Delta T}{\Delta t_h} \quad [4]$$

where k is thermal conductivity; ρ is density; c is heat capacity; T is temperature; and the subscript h refers to heat flow.

Equations [3] and [4] are not similar in their present forms. In order to bring these two equations into similar forms, make the substitution

$$\Delta\phi = \frac{k}{k_0}\Delta T \quad [5]$$

where the subscript 0 refers to a reference temperature (taken arbitrarily to be 0 F in the work described in this paper). Equation [4] then takes the form

$$\frac{\Delta^2\phi}{\Delta x_h^2} = \frac{1}{\alpha}\frac{\Delta\phi}{\Delta t_h} \quad [4a]$$

where α $(= k/\rho c)$ is the thermal diffusivity. Note that α is a known function of ϕ since α is a known function of temperature and temperature is related to ϕ by the integrated form of Equation [5]

$$\phi = \int_{T_0}^{T}\frac{k}{k_0}\,dT \quad [5a]$$

(See Fig. 2 for a curve of ϕ vs. T for SAE-1020 steel.) Write now Equation [3] in the form

$$\frac{\Delta^2 H}{\Delta x_f^2} = \frac{1}{\beta}\frac{\Delta H}{\Delta t_f} \quad [3a]$$

where β is equal to $A^2 g\Delta x_f/8\pi\nu\bar{A}$. Note that β can be made an arbitrary function of H since $\bar{A}$ can be made an arbitrary function of vertical distance in the hydraulic capacitors. Consequently, if the relationship between β and H is chosen properly, then a complete analogy exists between the aforementioned liquid flow and one-dimensional transient heat flow.

It remains now to be shown that boundary conditions which are found in thermal systems can be simulated in hydraulic systems. Consider first a thermally insulated surface. This boundary condition is simulated merely by a plugged tube through which no liquid can pass.

Consider next an aerodynamically heated surface. This boundary condition is described by

$$q_w = h(T_r - T_w) = -k_w\left.\frac{\Delta T}{\Delta x_h}\right|_w \quad [6]$$

Here h is the heat transfer coefficient; T_r is the recovery temperature; and the subscript w refers to the interface between the wall and the gas stream. For convenience, rearrange Equation [6] in the form

$$q_w = h\left(\frac{T_r - T_w}{\phi_r - \phi_w}\right)(\phi_r - \phi_w) = -k_0\left.\frac{\Delta\phi}{\Delta x_h}\right|_w \quad [7]$$

The analogous condition in the hydraulic system is described by

$$Q_w = \frac{A_{bl}^2 g}{8\pi\nu x_{bl}}(H_r - H_w) = -\left.\frac{A^2 g}{8\pi\nu}\frac{\Delta H}{\Delta x_f}\right|_w \quad [8]$$

Here A_{bl} is the cross-sectional area and x_{bl} is the length of the tube used to simulate the thermal boundary layer. Consequently, heat flow through a boundary layer into an aerodynamically heated surface can be simulated by liquid flow through one tube (having no distributed capacitance) into a second tube (having distributed capacitance) provided that

proper dimensions are chosen for the tube which simulates the thermal boundary layer. Note that a variation of the heat transfer coefficient with time can be simulated by a variation of the tube length x_{bl} with time; a variation of the recovery temperature with time can be simulated by a variation of the hydraulic head H_r with time.

Surface fusion can be simulated by allowing liquid to flow out of the appropriate tower (perhaps through a hole in the side of the tower) at the height H corresponding to the melting temperature of the structural material. When a quantity of liquid has overflowed which is equivalent to the quantity of heat required to melt the thickness of material represented by one element of the hydraulic system, the liquid flow would be by-passed around this element of the hydraulic system to simulate the removal of a corresponding layer of structural material. The quantity of liquid which should be permitted to overflow is calculated using the ratio

$$\frac{\text{liquid quantity}}{\text{heat quantity}} = \frac{\bar{A}\Delta H}{\rho c \Delta x_h \Delta T}$$

or, since $k \Delta T = k_0 \Delta \phi$

$$\frac{\text{liquid quantity}}{\text{heat quantity}} = \frac{\bar{A}\alpha}{k_0 \Delta x_h} \frac{\Delta H}{\Delta \phi}$$

Note that $\Delta H/\Delta\phi$ is merely a proportionality constant whose magnitude is selected for convenient computer operation. (It is shown in Section 3 in this paper that it is convenient to hold constant the product $\bar{A}\alpha$ also.)

Consider now the radiation of heat from the wall. This boundary condition may be simulated by the removal of liquid at the proper rate from the hydraulic capacitor which corresponds to the surface of the heated structure. The rate of liquid removal divided by the rate of heat removal is given by the expression

$$\frac{\text{liquid-removal rate}}{\text{heat-removal rate}} = \frac{\bar{A}\Delta H}{\Delta t_f} \Big/ \frac{\rho c \Delta x_h \Delta T}{\Delta t_h}$$

$$= \frac{\bar{A}\alpha}{k_0 \Delta x_h} \frac{\Delta H}{\Delta \phi} \frac{1}{\eta_t}$$

where η_t is the time constant which is defined by the relation

$$\Delta t_f = \eta_t \Delta t_h$$

The rate of liquid removal may be controlled manually (using perhaps a valve) or automatically (using perhaps holes drilled in the side of the appropriate tower to permit liquid to escape at a rate proportional to the fourth power of temperature).

Following the patterns thus outlined, it could be shown that other types of heat flow (e. g., two-dimensional heat flow) and other types of boundary conditions (e. g., the boundary condition which occurs when heat flows directly from one solid into another solid) could be simulated in the hydraulic system. Space will not be taken up here to discuss these other analogies.

Summarizing, the analogy between one-dimensional heat flow and flow of a liquid through a tube with axially distributed capacitors has been shown theoretically. The analogy was extended then to include certain boundary conditions which occur in problems involving aerodynamic heating. Thus it was shown that it is possible to solve many problems involving heat flow by observing liquid flows.

3 Design of Hydraulic Analog Computer

The design of a hydraulic analog computer, based upon the analogy described in Section 2, will be discussed in this section. Space and time transformations will be discussed first. Then details of the wall simulator, thermal boundary layer simulator, and recovery-temperature simulator will be considered, followed by a discussion of design factors such as pressure drop in connecting tubes, fluid momentum, and fluid turbulence. Finally, a comparison (for a sample problem) of hydraulic analog computer results with analytic results will be presented.

It is convenient usually to have the length of the liquid-flow path differ from the length of the heat-flow path and to have the length of the liquid-flow time differ from the length of the heat-flow time. Consequently, introduce space and time transformations through the two defining equalities

$$\Delta x_f = \eta_x \Delta x_h \quad [9]$$

$$\Delta t_f = \eta_t \Delta t_h \quad [10]$$

Substituting from these two defining equations into Equation [3a], one obtains

$$\frac{\Delta^2 H}{\Delta x_h^2} = \frac{\eta_x^2}{\eta_t} \frac{1}{\beta} \frac{\Delta H}{\Delta t_h} \quad [3b]$$

Inspection of Equations [4a] and [3b] reveals now that the two flows are analogous only if

$$\frac{\eta_x^2}{\eta_t} \frac{1}{\beta} = \frac{1}{\alpha} \quad [11]$$

or, in alternative form, if

$$\frac{\eta_x}{\eta_t} = \frac{\pi g \Delta x_h d^4}{128 \nu \bar{A} \alpha} \quad [11a]$$

where d is the tube diameter. Inspection of this relation emphasizes that variations of thermal diffusivity with temperature may be simulated by varying the cross-sectional area of the hydraulic capacitor with vertical distance, i. e., with hydraulic head. Parameter values typical of those values used in the computer which was built included

Δx_h = 0.05 in.
d = 0.101 in.
ν = 1.025×10^{-5} ft²/sec (water at 72 F)
$\bar{A}_0$ = 0.75 sq in. (corresponding to H = 0 in.)
α_0 = 1.58×10^{-4} ft²/sec (SAE-1020 steel at 0 F)

Inserting these values into Equation [11a], one obtains $\eta_x/\eta_t = 1.96$; η_t was chosen to be 50 and η_x was computed then to be 98. This choice meant that 1 sec of heat flow time was analogous to 50 sec of water-flow time, and that 1 in. of heat path was analogous to 98 in. of water path. These time and length transformations were found subsequently to be satisfactory.

The wall simulator consisted of a hydraulic resistance (a capillary tube) and hydraulic capacitances (water towers). The capillary tube was divided arbitrarily into ten equal parts, and one tower was attached to each tube increment (see photograph of breadboard model presented in Fig. 2).

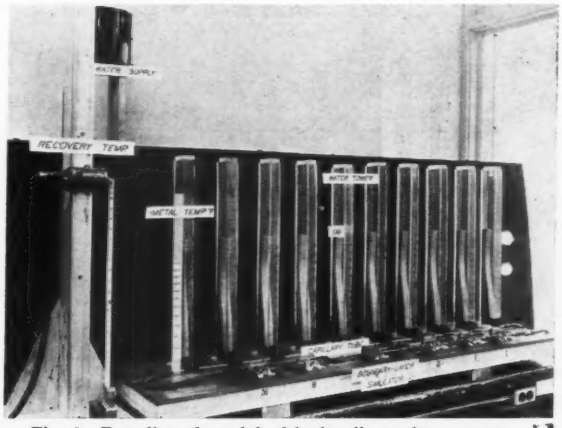

Fig. 2 Breadboard model of hydraulic analog computer

As mentioned in the preceding paragraph, the diameter of the capillary tube was chosen arbitrarily to be 0.101 in. The length of the tube was calculated from the length of the heat transfer path and the value of the space scale factor η_x. For example, for a heat transfer path of 0.50 in. and a space scale factor of 98, a tube length of 49 in. was computed. The variation of the cross-sectional area of the tower with thermal diffusivity was calculated from Equation [14a] holding all parameters except $\bar{A}$ and α const; i.e., from

$$\bar{A}\alpha = \text{const} \quad [12]$$

The value of this constant was calculated from the arbitrarily selected values of $\bar{A}_0$ and α_0 mentioned in the previous paragraph. The variation of the cross-sectional area of the water tower with vertical distance (i. e., with hydraulic head) was established by determining the relationship between $\bar{A}$ and ϕ and selecting (arbitrarily) then the proportionality constant between ϕ and hydraulic head H. The cross-sectional area $\bar{A}$ is related to ϕ by Equation [12], experimentally determined relationships between α and T, and Equation [5a]. The proportionality constant between ϕ and H was fixed by letting $H = 0$ correspond to $\phi = 0$ and by letting $H = 20$ in. correspond to the value of ϕ which one obtains for $T = 2000$ F. Varying the area $\bar{A}$ with vertical distance was accomplished physically by setting appropriately cut cams into the towers (Fig. 3).

The design of the thermal boundary layer simulator (Fig. 3) was based on the analogy which is obtained when Equations [7] and [8] are made similar. These two equations are similar when

$$\frac{\Delta\phi_w}{\phi_r - \phi_w} = \frac{\Delta H_w}{H_r - H_w} \quad [13]$$

Equations [7], [8], and [13] are compatible if

$$\frac{l_{bl}h}{k_0} = \left(\frac{d_{bl}}{d}\right)^4 \frac{\phi_r - \phi_w}{T_r - T_w}\eta_x \quad [14]$$

If computations are to be made for a surface which is heated aerodynamically, then two time-dependent parameters exist in Equation [14]: the heat transfer coefficient h, and the ratio $(\phi_r - \phi_w) / (T_r - T_w)$. Since h is not a rapidly varying function of T_w, one can determine h to good approximation by using estimated values of T_w if the vehicle trajectory is known. (Small errors made by calculating h in this manner may be taken into account by iterating; i.e., by calculating new values of h using values of T_w obtained with the computer.) The ratio $(\phi_r - \phi_w)/(T_r - T_w)$, however, cannot be predetermined accurately as a function of time since its value depends directly upon an unknown wall temperature. Inspection of a curve of ϕ vs. T (Fig. 3) reveals, fortunately,

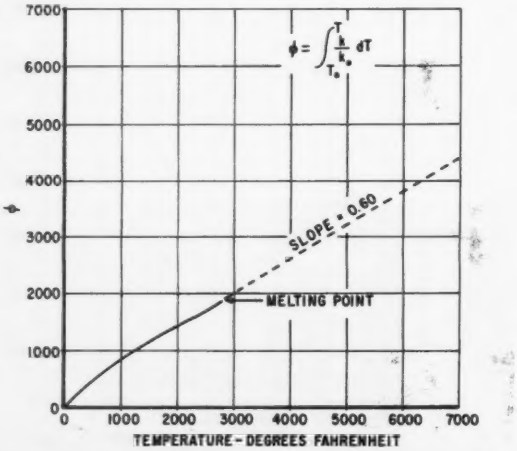

Fig. 3 The parameter ϕ as a function of temperature for SAE-1020 steel

that only small errors (of the order of 1 per cent) are introduced usually if one approximates the value of this ratio by a constant value. This approximation was used subsequently in preparing the program for the boundary layer simulator. Parameter values used for a 0.50-in.-thick skin of SAE-1020 steel included

$$\left(\frac{d_{bl}}{d}\right)^4 = \left(\frac{0.060}{0.101}\right)^4 = \frac{1}{8}$$

$$(\phi_r - \phi_w)/(T_r - T_w) = 0.60$$

$$\eta_x = 98$$

Inserting these parameter values into Equation [14], one obtains the following relationship between the capillary length of the boundary layer simulator and the heat transfer coefficient for the boundary layer

$$\frac{l_{bl}h}{k_0} = 7.35$$

(Note that for SAE-1020 steel, $k_0 = 0.00888$ Btu/ft sec °R.) Provisions were made for varying at will the effective length of the capillary in the boundary layer simulator by including in this simulator five tubes having lengths in the ratios 1:2:4:8:16 and by connecting these tubes with valves in a manner such that any desired effective tube length which is a multiple of 2.785 in. up to 89.120 in. could be obtained. From the vehicle trajectory data, the heat transfer coefficient was calculated then for several values of trajectory time. The equivalent length of the capillary tube in the boundary layer simulator was calculated, and a curve of l_{bl} vs. time was constructed using Equation [14]. This continuous curve was approximated then by a stepped curve, the ordinates of the steps being selected to coincide with multiples of 2.785 in., in order to correspond with steps which can be handled by the simulator. A schedule of valve settings finally was made which prescribed all changes made in the hydraulic resistance of the boundary layer simulator during the computer operation.

The recovery-temperature simulator (Fig. 3) consisted of a water-supply system which was designed to supply water at a prescribed head to the boundary layer simulator. Included in the water-supply system were a storage bottle, a modified automobile carburetor, and a scale to facilitate setting of the water head. A relationship between hydraulic head and recovery temperature was obtained by extending (as a straight line) a curve of ϕ vs. T beyond the melting point of the wall material and then using the proportionality constant between ϕ and H which was established previously. A schedule of hydraulic heads (carburetor settings) was made finally which prescribed changes to be made in the hydraulic head supplied by the recovery-temperature simulator during the computer operation.

In the selection of the dimensions of the several components of the computer, several design limitations were imposed in order to insure that the assumptions upon which the analogy was based were not violated and to insure that sources of large errors were not built into the equipment. Since the analogy was made assuming that the liquid flow was laminar, the computer was designed so that a Reynolds number of 2000 was never exceeded by the flowing liquid. Also, since the introduction of appreciable extraneous hydraulic-head losses would introduce appreciable errors in the computer results, the dimensions of valves and connectors were restricted as indicated by the relation

$$\left[\frac{\text{length}}{\text{diameter}^4}\right]_{\text{connector}} \ll \left[\frac{\text{length}}{\text{diameter}^4}\right]_{\text{capillary tube}}$$

Furthermore, since the analogy was made without admitting the existence of momentum losses (i.e., tube entrance and tube exit losses), the ends of the capillary tubes were flared,

and computations were made only after it was shown that the losses which were realized introduced only small errors in the computer results. (Further discussion of this last design limitation will be included in the next paragraph.)

As a check on the design of the hydraulic analog computer, a comparison was made (for a sample problem) of computer results with analytic results. The problem used was the heating of a flat plate (which plate was originally at uniform temperature) as the result of a sudden change of the environment temperature. This problem is so simple that analytic solutions are available (4, p. 284) and is at the same time so similar to guided missile aerodynamic heating problems that this check is realistic. The following parameter values (of the order of magnitude of parameter values encountered in aerodynamic heating calculations) were assumed to exist

k = 0.00888 Btu/ft sec °R
h = 0.1 Btu/ft² sec °R
$a = 1.58 \times 10^{-4}$ ft²/sec
s (one half of the plate thickness) = 0.5 in.

(Note that one half of the plate thickness for the sample problem is similar to the entire plate thickness for the aerodynamic heating problem since in the sample problem both surfaces of the plate are heated, whereas in the aerodynamic heating problem one surface of the plate is heated and the other surface is assumed to be insulated.) Taking the diameter of the tube in the boundary layer simulator to be 0.060 in., the length of this tube was calculated using Equation [14] to be 13.05 in. (Note that, since property values were assumed to be constant for this problem, the value of the parameter $(\phi_r - \phi_w)/(T_r - T_w)$ equaled unity.) A comparison of the results is presented in Fig. 4, where computer results are plotted on the ordinate and analytical results are plotted on the abscissa. Hydraulic analog computed results are approximately 5 per cent lower than analytical results. Since the values of the Reynolds numbers (1530 or less) were such that the water flows were laminar, and since the momentum losses were computed to be appreciable relative to the friction losses, this discrepancy between the computed and the analytical results was attributed to momentum losses. Although this discrepancy could have been eliminated either by decreasing the liquid Reynolds number or by increasing the length-to-diameter ratio of the capillary tubes, its value was so small that the computer was not redesigned before aerodynamic heating calculations were made.

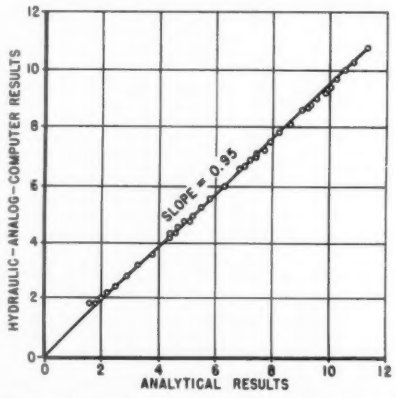

Fig. 4 Comparison (for the sample problem) of hydraulic analog computer results with analytical results

4 An Application of the Hydraulic Analog Computer

The afore-mentioned hydraulic analog computer was applied to the problem of determining the temperatures in $^1/_4$-in. and $^1/_2$-in. SAE-1020 steel walls which were heated aerodynamically. The aerodynamic environment of these walls was fixed by assigning a typical trajectory to a ballistic body entering the earth's atmosphere and studying one point on the nose cone of this body. The properties of the wall material were taken to be those properties presented as Fig. 5.

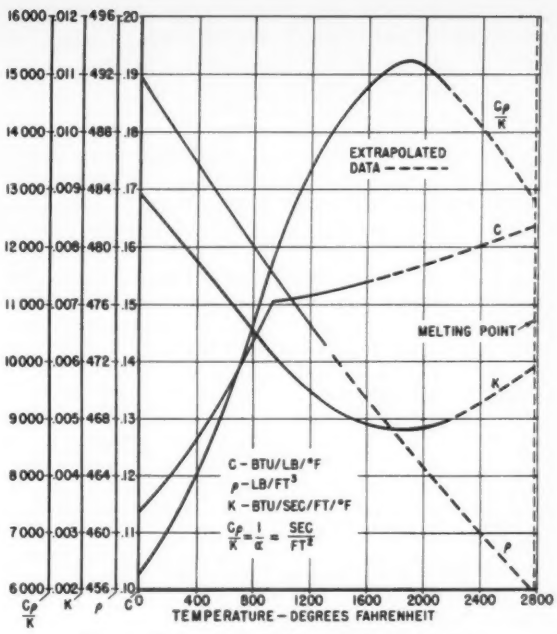

Fig. 5 Thermal properties of SAE-1020 steel

The boundary layer heat transfer coefficients and the recovery temperatures were calculated in a fashion similar to that described in Eckert's survey of aerodynamic heat transfer (5). As a first approximation, the wall temperature was assumed to vary linearly from 90 F to 1150 F during the trajectory through the earth's atmosphere. The small errors which were introduced by the inaccuracies of this guess could be eliminated by an iterative process wherein results obtained from using the first approximation would be used to obtain the boundary layer heat transfer coefficient for the second approximation, etc. The velocities, temperatures, and fluid properties corresponding to the stream immediately outside the boundary layer were calculated using the MIT tables for supersonic flows around cones at zero

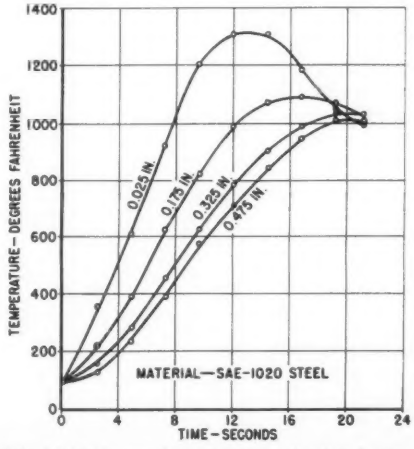

Fig. 6 Calculated temperatures for several points in the skin of a cone entering the earth's atmosphere (thickness = 0.50 in.)

angle of attack (6). On the basis of results of preliminary checks, radiation from the walls was neglected.

After the heat transfer coefficient and recovery temperature were determined as a function of time, schedules for the operation of the boundary layer simulator and the recovery temperature simulator were made in the manner described in Section 2. During the computer operation, the length of the capillary tube in the boundary layer simulator and the setting of the carburetor was varied according to the prescribed schedule. The height of the water in the ten hydraulic capacitors (Fig. 3) was read visually and recorded manually at preselected intervals during the computer operation. After the computer operation was completed, the hydraulic heads which were recorded during the operation were converted into temperatures using the relationships described in Section 2. Data obtained using this hydraulic analog computer are presented in Figs. 6 through 9.

5 Conclusions

The calculations which were made for the aerodynamically heated steel walls have emphasized the following important and useful features of the hydraulic analog computer:

1 Variations of recovery temperature and boundary layer heat transfer coefficient with time may be accommodated easily.

2 Variations of thermal properties of the wall material with temperatures may be handled simply.

3 A clear physical picture of the temperature variations with space and time is obtained by observing the computer during its operation.

Future models of the computer could be adapted readily to include the following features:

1 Two- and three-dimensional heat flow could be investigated by using additional banks of hydraulic capacitors interconnected by capillary tubes.

2 Melting of the wall surface could be simulated by making provisions for removing water from the hydraulic capacitors to stimulate the absorption of the latent heat of fusion by the melting material.

3 Surface erosion could be investigated by using by-pass valves to short-circuit the hydraulic capacitors and resistors as erosion progresses.

4 Radiation of heat from the wall surface could be simulated by the removal of fluid at the proper rate from the junction of the boundary layer simulator and the wall simulator.

5 If the thermal conductivities of the several materials can be assumed to vary similarly with temperature, then heat transfer through a wall consisting of several laminae (each lamina having thermal properties which differ from those of the adjacent lamina) could be simulated. The wall simulator would be divided into sections (each section corresponding to one lamina), and the dimensions of the capillary tubes and of the cams in each section would be selected to correspond with the thermal properties and physical dimensions of the corresponding lamina.

These realized and potential features of the hydraulic analog computer make this computer a very versatile, useful, and economical tool for the design of structures subjected to severe aerodynamic heating.

Acknowledgments

The authors wish to express their appreciation to Dr. Hans Schuerch for taking part in technical discussions pertaining to the work described herein. Dr. Adam Zahorski, Chief of the Structures Section, showed a continued interest in the development program.

(*Continued on page 659*)

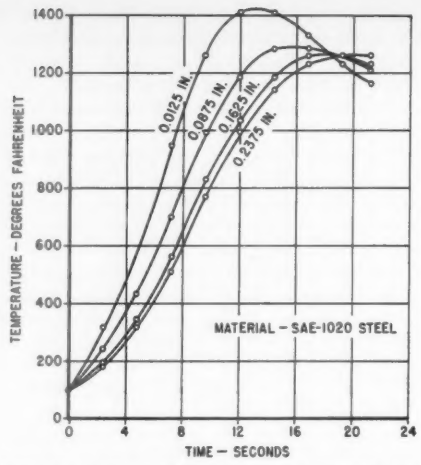

Fig. 7 Calculated temperatures for several points in the skin of a cone entering the earth's atmosphere (thickness = 0.25 in.)

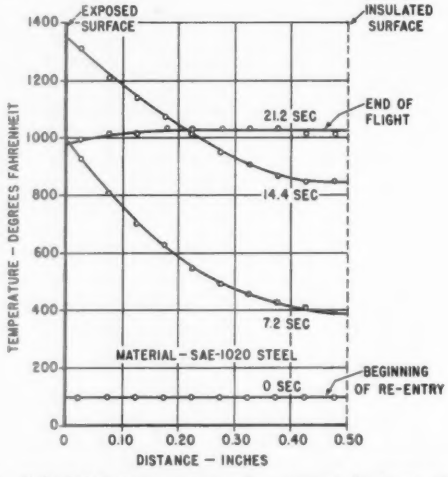

Fig. 8 Calculated temperatures for several instants of time during re-entry into the earth's atmosphere of a cone (thickness = 0.50 in.)

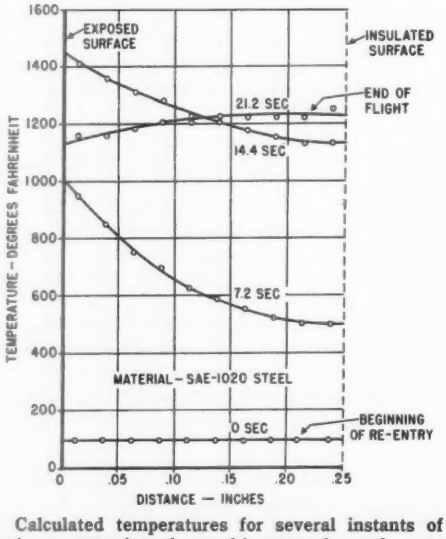

Fig. 9 Calculated temperatures for several instants of time during re-entry into the earth's atmosphere of a cone (thickness = 0.25 in.)

Observations on the Irregular Reaction of Solid Propellant Charges[1]

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A review of development experience and research studies concerning reaction irregularities in solid propellant rocket motors emphasizes a difference in usage of the equivocal term "unstable burning" by the rocket designer on the one hand and the theoretical investigator on the other. Evidence is presented indicating that high frequency pressure oscillations of finite amplitude can prevail in the charge cavity during outwardly "stable" operation. A possible coupling mechanism by which gas phase oscillations may effect exaggerated rates of solid phase decomposition is suggested in qualitative terms.

Nomenclature

J = ratio of nozzle throat area to area of charge port
K = ratio of propellant surface area to nozzle throat area
k = erosive burning constant in terms of linear gas velocity, $r/r_0 = 1 + kv$
m = exponent governing rate at which gaseous reactants are assumed to be activated during the time interval τ according to the Cheng theory

$$\int_{t-\tau}^{t} p^m (t')\, dt' = \text{const}$$

n = exponent of the conventional steady-state, zero-velocity burning rate law, $r_0 = cp^n$
p = pressure
r = linear burning rate
r_0 = burning rate in absence of parallel gas velocity
S = over-all pressure index of interaction in Cheng theory $S = m - (n/2)$
t = time
τ = time lag (of various reactions)
v = space-mean, time-average linear gas velocity parallel to burning propellant surface

Introduction

BRITISH investigations of "secondary peaks" in the pressure vs. time curves exhibited by tubular charges of cordite appear to constitute the first studies of unstable burning, in solid propellant rocket motors. The term "secondary peak" was used to distinguish the abrupt, irregular increases in chamber pressure characteristic of unstable burning, from the initial pressure peak resulting from sharp igniter operation or erosive burning of the propellant. Subsequent experience has shown that the secondary irregularities can, occur either early or late in the pressure-time history, the point of occurrence apparently depending upon the operating conditions (pressure level and propellant temperature) and the charge design (grain configuration and throat to port area ratio J). These irregularities are more severe in charges of high length/diameter ratio than in "short" ones. The phenomenon has been observed in motors of all diameters and has been exhibited by all the major high energy propellant systems. Some typical examples of irregular reaction in charges of three conventional configurations are shown in Fig. 1.

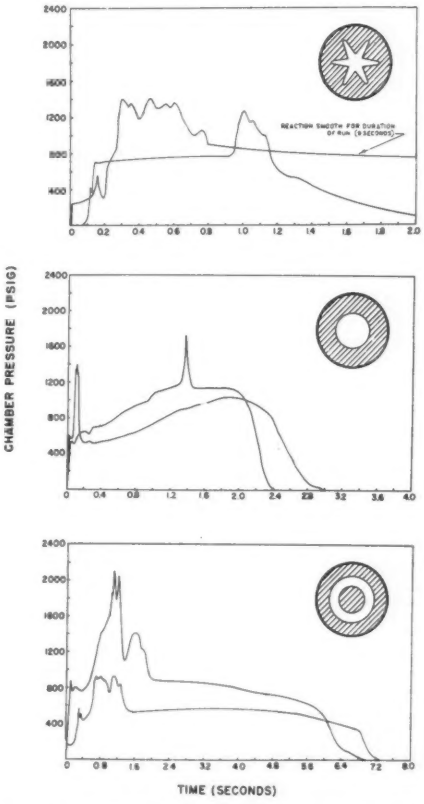

Fig. 1 Typical examples of irregular reaction in internal-burning charges of high energy composite propellant employing star-shaped, cylindrical, and annular perforations

Early Development Experience

The charge in which unstable burning was first noted was a tubular grain burning on both its inner and outer surfaces. Boys and Schofield (1)[3] reported that secondary peaks in the firing of cordite charges were always accompanied by localized abnormal burning in the axial perforation, the propellant surface in such regions being heavily rippled or pitted, and the amount of propellant burned away being excessively large. Noting U. S. experience that tubular grains supported by axial trap wires burned smoothly, they showed that stabilization could be accomplished by providing either a rod or a flat

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Presented at the ARS 25th Anniversary Annual Meeting, Chicago, Ill., Nov. 14–18, 1955.

[1] This paper is based on a survey supported by the United States Air Force through the Office of Scientific Research of the Air Research and Development Command.

[2] Principal Engineer, Nuclear Projects Dept. Mem. ARS

[3] Numbers in parentheses indicate References at end of paper.

"tongue" along the axis of the grain perforation. In a brief series of tests, they also found that stability was promoted by providing the grain web with radial holes, open to the inner perforation only, which during burning served to generate jets of gas directed normally to the main stream. The effectiveness of rod stabilization of small tubular charges of JPN ballistite was confirmed by investigators at the California Institute of Technology (2), who also found that locally stable reaction was obtained if the grains were provided with radial perforations extending completely through the grain web or, in the limit, a longitudinal slot through the web.

In view of these results, it became apparent that the secondary pressure peaks were associated with a flow phenomenon occurring in the central grain cavity. Noting from observation of partially burned grains that the heavily eroded regions appeared "as if the gas were swirling with a high velocity," Boys and Schofield concluded directly that "abnormal burning is due to some abnormal gaseous flow or oscillation." Using more guarded language, Ferris et al. (3) attributed the enhanced burning rate to an erosive burning mechanism: "It is reasonable to expect that the presence of disturbances in the gas flow would cause an increase in the burning rate at constant pressure within the axial perforation." Owing to the general belief that the occurrence of secondary peaks was associated with an oscillatory flow condition, unstable burning came to be loosely known as "resonance," although the actual existence of oscillations was not verified until later.

Descriptive and Analytical Investigations

The experience summarized above was obtained from tests concerned primarily with the practical development of specific rocket motors. In addition, the mechanism of unstable burning of solid propellants has been the subject of fundamental investigations, both theoretical and experimental. The pioneer theoretical efforts, made by H. Grad and J. K. L. MacDonald at New York University, concluded that the "resonance" phenomenon was indeed associated with the occurrence of acoustical oscillations within the (cylindrical) grain cavity. The existence of high-frequency pressure oscillations in rocket motor firings was first confirmed in 1948 by experiments at the Naval Ordnance Test Station, but following the death of MacDonald the program was terminated before specific modes were identified. Following publication of the Grad theory (4), a systematic experimental study aimed at describing the phenomenon was conducted by Smith and Sprenger (5), who concluded that serious reaction instability in grains with cylindrical and annular perforations was accompanied by oscillations of frequencies corresponding closely to those of the pure tangential modes. In some cases only the fundamental tangential mode was observed, while in others the first five longitudinal modes could be identified. Longitudinal waves were not found to be associated with gross irregularities in the pressure-time history. More recently Cheng (6) has presented a theory of unstable solid propellant combustion extending that of Grad, and Moore and Maslen (7) have analyzed the buildup of transverse resonance in a cylindrical combustor in a generalized manner which includes the solid propellant problem as a special case. Of these several theories regarding the mechanism by which the oscillations are sustained, that advanced by Smith and Sprenger has been stated only descriptively, while the others enjoy elegant analytical expression. For the purpose of the present cursory review, the salient features of each will be briefly compared in qualitative terms. The detailed structures of the Grad and Cheng theories have recently been compared by Geckler (8).

Assuming the burning rate of the solid propellant to be a function of the pressure and temperature of the combustion gases, Grad (4) analyzed the conditions under which originally infinitesimal pressure oscillations are amplified. The mechanism investigated was this: "A small pressure rise near the powder grain leads to a local increase in mass flux, thereby increasing the pressure disturbance; this leads to a further increase in mass flux, etc., and possibly eventually to a cumulative blow-up." A high pressure sensitivity of burning rate (i.e., a high value of the pressure exponent n) would thus promote instability. Grad also postulated a constant time lag in this solid propellant burning rate; i.e., that the rate at which the solid phase decomposes at any given instant t depends upon the conditions of gas pressure and gas temperature which prevailed at a previous instant $t - \tau$. This attack was successful in that the acoustical mode predicted to be most susceptible to amplification ("waves spiraling around the inside of the grain, more or less sticking to the inner surface of the grain and in this way emphasizing the boundary condition at the burning wall") was later found to be associated with the more serious mean-pressure irregularities observed in the experiments by Smith and Sprenger mentioned above. Subsequent to Grad's study, however, unstable burning has been observed with propellants operating upon a burning rate "plateau" (a region where the burning rate is nominally independent of pressure, at least in the steady state), and it is not possible to explain this behavior by means of Grad's self-excitation mechanism. Also, Grad advanced no mechanism by which the average value of the propellant burning rate is increased by the occurrence of acoustical wave motion.

In addition to providing the first experimental description of the wave motion which gives rise to irregular burning, Smith and Sprenger also suggested a mechanism by which self-excitation and sustenance of this motion could be effected by the gas phase reaction alone: A small-amplitude acoustical oscillation, initiated by some minor disturbance, causes periodic fluctuations in pressure and temperature within the zone of the gas phase combustion reaction; these fluctuations induce sympathetic fluctuations in rate of heat liberation by the reaction; if there is no significant time lag in the process, extra heat is liberated in phase with the pressure increase and less heat is liberated during the rarefaction phase; the periodicity in the heat liberation amplifies the oscillation, in accordance with Rayleigh's principle.[4] The increase in average burning rate observed during unstable burning is then attributed to the increased rate of heat transfer from the hot combustion gases to the solid propellant promoted by the lateral gas motion parallel to the burning surface, as originally conceived by the early investigators.

The writer subscribes to the belief that the acoustical wave motion is sustained by a gas phase reaction, and that augmented convective heat transfer increases the propellant burning rate. Tangential oscillations are also often observed in liquid propellant rocket engines, for instance, and can give rise to local melting of the combustion chamber or injector. Nevertheless, the increase in solid propellant burning rate provided by erosive burning effects does not alone seem sufficient to explain the highly exaggerated mean pressures which are sometimes experienced during unstable operation. For example, a pressure-time curve obtained by Smith and Sprenger with a long tubular charge (high exit velocity) is represented in Fig. 2. Since the abrupt pressure rise seen therein is immediately followed by an equally precipitous drop, fracture of the grain at that instant is not indicated. On the other hand, if the steady-state plateau ballistics of the propellant (also shown) are valid in the nonsteady state, it would appear that the several-fold increase in mean pressure cannot be attributed to erosive burning alone. Assuming that the simple linear erosive burning law $r/r_0 = 1 + kv$ is accurate at high velocities,[5] it may be estimated from the known

[4] Rayleigh's principle states that acoustical oscillations can be sustained and amplified by the periodic addition of heat in phase with pressure variation.

[5] This approximation actually overestimates the erosive effects at high gas velocities.

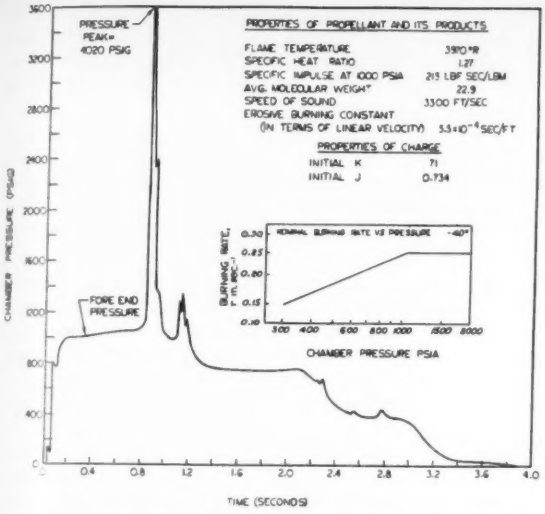

PRESSURE PEAK = 4020 PSIG
PROPERTIES OF PROPELLANT AND ITS PRODUCTS
FLAME TEMPERATURE 3970°R
SPECIFIC HEAT RATIO 1.27
SPECIFIC IMPULSE AT 1000 PSIA 215 LBF SEC/LBM
AVG. MOLECULAR WEIGHT 22.9
SPEED OF SOUND 3300 FT/SEC
EROSIVE BURNING CONSTANT (IN TERMS OF LINEAR VELOCITY) 5.5×10⁻⁴ SEC/FT
PROPERTIES OF CHARGE
INITIAL K 71
INITIAL J 0.734
FORE END PRESSURE
NOMINAL BURNING RATE VS PRESSURE -40°
BURNING RATE, IN./SEC
CHAMBER PRESSURE PSIA
CHAMBER PRESSURE (PSIG)
TIME (SECONDS)

Fig. 2 Firing curve obtained with an internal-burning tubular charge (52 in. long, 1 in. ID) of composite propellant at −40 F

erosion properties of the propellant that an effective time-average, space-mean gas velocity of about 5100 fps (or approximately 2.4 times the stagnation speed of sound) would be required to effect the pressure increase observed. The writer suggests that an alternative explanation may possibly lie in a coupling between the temperature-sensitive surface decomposition reaction in the nonsteady state and the gas phase oscillations, in a manner outlined later.

The stability of small periodic disturbances superposed on the steady-state gas flow in a solid propellant rocket has been studied by Cheng (6), who postulated a time lag in the gas phase combustion reaction; i..e, that gases generated by decomposition of the solid at the instant t will burn instantaneously and completely at the instant $t + \tau$. He also assumed that the rate of solid decomposition and of final combustion product generation, as well as the variation of the time lag between these events, is a function of pressure alone. This analysis predicts that the fundamental spiral mode (in variation of the charges with cylindrical or annular cavities) is the mode most susceptible to amplification, and indicates that the effect of gas velocity is not essential to the instability mechanism, although it can contribute to an increased burning rate once oscillations of finite amplitude have developed. The analysis also indicates that a simplified over-all pressure index of interaction $S = m - (n/2)$ must be greater than a certain minimum value S_{min} if unstable oscillation is to be possible. According to this result, stability is promoted by a high value of the pressure exponent n, a view conflicting with that of Grad. Furthermore, S_{min} for a cylindrical cavity is shown to be an increasing function of length/diameter ratio, whereas the reaction irregularities exhibited by tubular charges (as well as others) become more severe as the charge length is increased.

The amplification of weak transverse oscillations in cylindrical combustion chambers has been analyzed by Moore and Maslen (7) in a generalized manner applicable to several types of combustion systems. Combustion is assumed to take place in a thin annular section which performs mechanical work on the surrounding gases in proportion to the instantaneous pressure level. The analysis indicates that concentration of burning near the center of the combustor amplifies the radial mode of oscillation most strongly, while burning at the combustor wall amplifies the tangential ("sloshing") modes, the degree of amplification increasing with the order of the mode. For the case of burning at the wall, the presence of a nonburning centerbody (i.e., a resonance rod) decreases the amplification. Presence of a time lag between the temperature disturbance and the heat release rate in the annulus favors amplification of lower frequency modes; in particular, the first "sloshing" mode. It is indicated that the form of transverse waves does not undergo a progressive change leading to shock formation, as in one-dimensional flow; and that transverse modes are not inhibited by viscous effects to the same degree as are one-dimensional waves, and for this reason are perhaps better able to attain extreme amplitudes. These conclusions appear to be consistent with the experimental observations on resonance in solid propellant rocket motors.

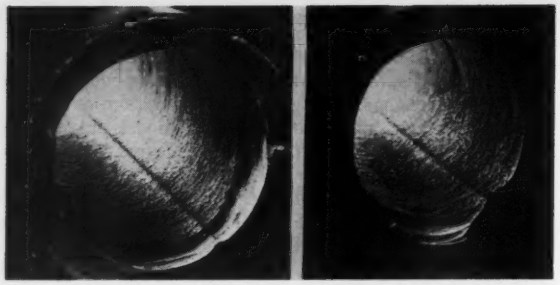
Terminology Distinctions

According to the admittedly loose original usage, the term "unstable burning" or "resonant burning," as applied to solid propellant rocket motors, refers to irregular pressure-time histories, with erratic "secondary peaks," as observed by a relatively low-frequency response instrumentation system which records only the mean value of a pressure oscillating at a frequency in the range of high pitched sound. On the other hand, the stability theories discussed above are concerned with the conditions under which the amplitude of a small acoustical oscillation can grow to a finite value. This ambiguous usage, which already has given rise to semantic difficulties (9, 10), has apparently resulted from tacit acceptance of the unsubstantiated premise that the occurrence of large-amplitude, high-frequency pressure oscillations is always accompanied by irregularities in the mean pressure level.

There is a significant amount of experimental information available which indicates that although the existence of high-frequency oscillations may be necessary for the occurrence of gross pressure peaks, it is not sufficient; i.e., oscillations of finite amplitude can prevail even during periods of outwardly "stable" operation. At this laboratory, in tests of a rocket using a low energy potassium perchlorate propellant which has never exhibited resonance, accelerometers attached to the motor detected longitudinal vibrations sustained throughout the run, vibrations which were attributed to "some instability in gas flow or propellant burning" (11). In firings of tube-in-shell charges of a mixed ammonium and potassium perchlorate propellant, smooth low-frequency response pressure-time traces were yielded by tests in which transverse oscillations of amplitudes ranging up to 200 psi were observed by high-frequency response instrumentation, while rough curves were exhibited by tests in which no oscillations of amplitude greater than 20 psi were detected; it appeared that the gross irregularities were associated with oscillations of a certain frequency (in this case apparently corresponding closely to the first tangential mode in the annular perforation) with amplitude being of secondary importance (12). Similar results were obtained in firings of rod-in-shell charges of high-energy ammonium perchlorate propellant; transverse oscillations of amplitudes up to approximately 1000 psi were observed[6] during periods of "stable" operation, while irregular peaks were observed at intervals when oscillations of amplitudes as low as 25 psi were prevailing (12). Interrupted burning experiments by Smith and Sprenger have furnished similar information; the erosion patterns visible on the partially burned grains shown in Fig. 3 indicate the occurrence of a tangential wave pattern in the grain perforation during both tests, but the pressure-time curve obtained in the second test was normal, as shown in Fig. 4.

Equivalent results have been obtained by at least one other laboratory. Tests of star-perforated charges of ammonium perchlorate propellants at the Jet Propulsion Laboratory have frequently revealed high-frequency oscillations prevailing during runs in which the mean chamber pressure did not deviate from its nominal value; oscillations of roughly 100 psi

[6] The nominal mean pressure level prevailing during these tests was also about 1000 psi.



Stopped after 1.5 sec, burned unstably

Stopped after 1.8 sec, smooth run

Fig. 3 Fore end views of partially burned tubular grains of high energy composite propellant

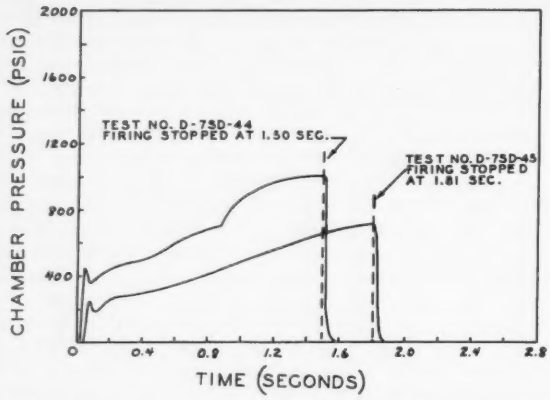


Fig. 4 Firing curve obtained in interrupted burning tests of grains shown in Fig. 3

amplitude and of frequencies presumably corresponding to tangential and radial modes were detected by high-frequency response pressure instrumentation (13). High-frequency response accelerometers attached to the fore end of the motors during these tests recorded extremely high acceleration values. Erosion patterns suggesting the presence of acoustical wave motion have also been observed in interrupted burning tests at JPL which yielded consistently "smooth" firing curves. The above observations suggest that the stability of a small pressure perturbation in the combustion gases within a solid propellant rocket motor, as considered by the theoretical analyses discussed earlier, does not necessarily influence the nominal "stability" of the motor operation, as conventionally[7] considered by the motor designer.

Hypothetical Coupling Mechanism

The foregoing discussion has noted that irregular reaction has been observed in grains of propellants with steady-state burning behavior nominally characterized by zero pressure dependence, and that normal reaction has been observed in tests during which acoustical oscillations of finite amplitude prevailed. A premise consistent with both these observations is that resonant burning (in the gross sense) arises from an increase in the rate of the solid-phase decomposition reaction under the proper condition of oscillatory heat transfer to the propellant surface. Since the phenomenon appears only in situations where an appreciable gas velocity obtains parallel to the burning surface, it is assumed that the critical variation in heat transfer is accomplished by a convective agency.[8] The burning rate of the propellant is assumed to be governed by an Arrhenius function of the surface temperature (16) but with a time lag in the reaction. It is suggested that in this highly idealized situation, a nonlinear increase in average burning rate may be effected by the following sequence of events:

1 The boundary layer controlling the rate of heat transfer from the hot stream to the cooler solid surface is momentarily thinned by the local increase in parallel velocity attending the passage of a transverse wave.

2 With the instantaneous rate of local heat transfer momentarily enhanced, the surface temperature prevailing at an instant t is increased, thus increasing the rate of propellant decomposition at a later instant $t + \tau$.

3 The increased flux of gas from the receding surface thickens the boundary layer, reduces the rate of heat transfer, and aided by an endothermic phase change cools the surface, thus again inviting an increased heat flux at a later instant.

On the basis of a simplified analysis of this situation (17) it appears that if the period of the parallel velocity (or heat transfer) oscillation and the time lag of the decomposition reaction are properly related, a periodic variation in surface temperature may be sustained, with the local "excess" of heat transferred to the surface by passage (at a given location) of a velocity loop producing a local "excess" of gas evolved and burned during passage of a following pressure loop. Although the mean surface temperature is not necessarily changed, the nonlinear nature of the Arrhenius rate relation can effect an increase in the mean burning rate.[9] The coupling mechanism postulated above assumes that the acoustical wave motion is sustained by the gas phase combustion reaction independently of the solid phase decomposition reaction; only when the time lag in the solid phase reaction and the frequency of the acoustical oscillation are properly matched does the "resonant" condition obtain and any increase in mean burning rate necessarily take place. To supplement the analytical evaluation of this proposition, it is suggested that detection of any periodic fluctuations in the surface temperature of a burning solid propellant might conceivably be accomplished experimentally by photographic viewing of the surface through an optical filter passing a narrow band of wave lengths corresponding to the mean surface temperature. At the present state of the art, however, accurate determination of even the steady-state temperature is difficult.

Acknowledgment

The writer wishes to acknowledge informative discussions with R. D. Geckler of the Aerojet-General Corporation, H. M. Shuey of the Rohm and Haas Company, and G. Robillard of the Jet Propulsion Laboratory.

[7] In guided missile applications, not only a "smooth" firing curve is required; consideration must also be given to the deleterious effect of combustion-sustained vibrations upon electronic components.

[8] The effect of longitudinal oscillations in main-stream velocity upon heat transfer has been investigated by Lighthill (14). In studying the effect of lateral oscillations, the solid propellant case may also be idealized by the boundary layer approximation. The propellant surface is represented as a flat plate with a stream velocity increasing linearly from zero at the leading edge. Burning of the propellant is simulated by a constant injection velocity, and a sinusoidal velocity component parallel to the plate, but normal to the stream direction, is superposed upon the main flow. The resulting nonsteady, 3-dimensional boundary layer problem has been formulated (15), but is difficult to solve, even when simplified by the assumption of incompressible flow. This problem is currently under investigation.

[9] The mechanism here postulated should be distinguished from that suggested by Geckler (18), who considered the effect of a temperature-dependent heat release term in the solid phase conduction equation upon the stability of the damped temperature wave in the solid resulting from oscillatory heat flux to the surface. He pointed out that if the reaction were exothermic, the wave would be amplified, while it would be damped if the reaction were endothermic, and suggested that the sign and magnitude of the heat release term might thus influence the combustion stability of the propellant. The effects of the solid phase heat release term are here considered contributory, rather than essential, to the mechanism suggested.

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Application of Hydraulic Analog Method

(*Continued from page 654*)

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Ten Years of Project SQUID—A Bibliography

Introduction

THOUGH it may come as a surprise to the many who regard "squid" and "octopus" as synonymous, all of the many biological varieties of the species squid have ten tentacles. Consequently, this review might have been yclept "Decade of a Decapod." It is likely that such a title would have confused the reader at least as much as the aqueous smoke screen of the cuttlefish befuddles its prospective captives or captors. By whatever name, however, a tenth anniversary is something of an event. Therefore, Project SQUID welcomes the opportunity to review its history briefly in these pages. It seems appropriate in view of the fact that the Project, its crustacean namesake, and this JOURNAL all have an abiding interest in both jet propulsion and the secretion of ink.

Project SQUID began in the spring of 1946 as a cooperative venture on the part of the Navy Bureau of Aeronautics and five university laboratories. It was conceived as a device by which some of the talents of academic scientists could be brought to bear on some of the problems plaguing the development of pulsejet and liquid rocket engines. Over the years, SQUID's scope and emphasis have expanded and shifted. It now contemplates the support of research in any field of science which relates to the technology of jet propulsion. The properties of structural materials such as metals and ceramics are specifically excepted. In general, most of SQUID's activity has been concerned with combustion, fluid flow, and heat transfer. It has become somewhat more preoccupied with basic science and less active in development and application than in the early days. As a result, the amount of money required for the support of a particular investigation has on the average decreased while the number of programs has increased although the budget is smaller. There are now eleven universities, three companies, and two government laboratories in the SQUID family.

The sponsorship of SQUID has also sustained some changes. The Bureau of Aeronautics early transferred its role to the Office of Naval Research. For several years the Office of Scientific Research of the Air Force and the Office of Ordnance Research of the Army made substantial contributions. While these latter two agencies still act in an advisory capacity they have withdrawn their financial support so that all of SQUID's sustenance now stems from the Office of Naval Research through the Power Branch of the Material Sciences Division.

The administrative structure of SQUID is somewhat singular and deserves mention. It comprises a prime contract between the Navy and Princeton University. In turn, Princeton enters into subcontracts with the other participating groups. The financial accounting and paying, together with the formulation and execution of subcontract arrangements, are carried out by Princeton. Technical monitoring, guidance, proposal evaluation, and report reproduction and distribution are the responsibility of a Headquarters staff employed by Princeton. The responsible authority for decisions relating to technical program and policy is vested in a Steering Committee made up of representatives from the three armed services and the National Advisory Committee on Aeronautics. Security matters, property accounting and control, and cost inspection are the responsibility of government representatives located near the contractor. These include particularly the ONR branch offices as well as resident representatives of various agencies, cost inspectors, and the like. It is apparent that the existence of a project like SQUID depends upon the smooth cooperation of a number of groups and individuals.

Because it caters particularly to university laboratories, SQUID has geared its fiscal year to the academic calendar. Thus, the subcontracts all normally run from October 1 to September 30. In order to permit the universities to plan the use of facilities and staff in the spring preceding the fall term, decisions on support are made by the Steering Committee and communicated to the subcontractors in April. These decisions are based on proposals submitted in written form in January and distributed to the Steering Committee and its consultants. The proposals are reviewed and discussed along with progress reports by present members of the SQUID family at an annual meeting usually held early in March. Immediately after the meeting, the Consultants and the Headquarters staff consider and evaluate each proposal in detail. On the basis of this consideration, Headquarters prepares a recommended program for the ensuing year. In turn, the Steering Committee, guided by Headquarters' recommendations and its own analysis, makes a final decision on each proposal.

The people who have been associated with SQUID in one way or another number in the hundreds. An attempt to list them all or to acknowledge their contributions would be futile. However, it may be of interest to identify the organizations which have participated technically in the SQUID program

Atlantic Research Corporation
Polytechnic Institute of Brooklyn
University of California at Berkeley
California Institute of Technology
Catholic University
Cornell Aeronautical Laboratory
Dartmouth College
University of Delaware
Experiment, Incorporated
Johns Hopkins University
Massachusetts Institute of Technology
University of Michigan
Naval Research Laboratory
New York University
Northwestern University
Princeton University
Purdue University
United States Bureau of Mines
University of Wisconsin

As a result of cooperation between these groups and the sponsors, more than three score and ten mature scientific investigators have received encouragement and financial support for their research. It is also a source of satisfaction, in these days of the shortage of technical manpower, that over 500 man years of employment training have been provided for students in the SQUID program.

During its existence, SQUID has done other things besides provide support for research investigations. From time to time it has sponsored a large number of conferences and symposia on various subjects, both classified and unclassified. It has maintained a library of reports on jet propulsion. It has made surveys of the state of the art in fields within its scope. Nevertheless, SQUID's primary mission has been to sponsor research in certain fields of science and engineering. Only by the fruits of this research can the accomplishments of SQUID be evaluated. But objective appraisal is difficult. The ultimate value of a piece of scientific research may not appear for years. Derived utility may not be realized for decades. Perhaps the best one can do is to present systematically a collection of references to technical reports and literature which have been generated in the programs supported by SQUID. The resulting bibliography may be of interest and use to readers of this JOURNAL. Many SQUID reports have been referred to in the open literature. Therefore, it may be worth while to have on record a complete list of all unclassified literature resulting directly from SQUID research. Accordingly, SQUID is most happy to take advantage of the opportunity provided by JET PROPULSION to publish a complete bibliography with abstracts of all unclassified SQUID technical publications and reports which have appeared before June 1, 1956. The task of judgment will be left to history.

A word about availability of copies of reports is in order. The majority of recent publications have appeared as technical papers in regular journals and present no great problem. Reprints are sometimes available from the authors. Government agencies and contractors may obtain full size or microcard copies of any SQUID report from ASTIA. All others should order them from the Office of Technical Services, Department of Commerce, Washington. With but few exceptions both ASTIA and OTS have complete files. Since October 1954 all regular SQUID publications, except progress reports, have been reproduced and distributed to the SQUID mailing list on microcards, whether or not they have or will have appeared in journals. However, *SQUID Headquarters is not authorized to send copies of reports to anyone not on its regular distribution list.* Exceptions can be made only when permission is obtained directly from the Power Branch, Code 429, Office of Naval Research, Department of the Navy, Washington.

The Bibliography is broken down into six main sections identified by Roman numerals. Subsections are indicated by letters. An author index is provided in which reference is by Roman numeral and letter to a particular section. Within each section the order of appearance is chronological. The number comprising a prefix of capital letters followed by a numeral and a suffix of capital letters is the SQUID identification number. The prefix indicates the contractor, the numeral its order of appearance, and the suffix the kind of article. In the suffix, M and R indicate a memorandum or report distributed only to the SQUID mailing list. The letter P indicates presentation or publication at large. The letter T indicates a thesis (available only on microcard). When there is more than one letter in the suffix, it indicates that the same material appeared in more than one form. For reasons of consistency, all the SQUID reports were renumbered in preparing this Bibliography. Consequently, especially in the case of earlier reports, *the SQUID numbers appearing here may not be the same as those appearing on the reports themselves.* The numbers here are now official. Any questions about the numbering should be referred to Headquarters.

EDITOR'S NOTE: The printing and distribution of this manuscript in JET PROPULSION have been financed entirely by Project SQUID under Contract N6-ori-105, Task Order III, NA-098-038. It is included in this issue as a service both to Project SQUID and the membership of the ARS. Sponsored manuscripts are published from time to time at the cost of the sponsor if they are deemed of interest to ARS members.

Table of Contents

I Properties of Materials (Transport, Structural)
- A Gases
- B Liquids
- C Solids

II Physical Processes
- A Heat Transfer
- B Mass Transfer and Mixing
- C Fluid Flow

III Chemical Processes
- A Reaction Kinetics
- B Thermodynamics and Thermochemistry

IV Combustion Phenomena
- A Ignition
- B Flame Propagation Rate
  - (a) Laminar
  - (b) Turbulent
- C Flame Structure and Stability
- D Flame Spectra and Radiation
- E Miscellaneous

V Engines and Propulsive Systems
- A General
- B Air Breathing
- C Rockets

VI Instrumentation
- A Temperature Measurement
- B Pressure Measurement
- C Miscellaneous

I Properties of Materials (Transport, Structural)

A Gases

1 Heat Conductivity, Viscosity, Specific Heat and Prandtl Numbers for Thirteen Gases, by F. G. Keyes, Massachusetts Institute of Technology, April 1952, *MIT-2-R.*

Experimental effort is especially directed to obtaining measurements of heat conductivity at temperatures above the upper range of reported data. No measurements to temperatures approaching 1000 C are given. Results of several years of conductivity measurements for a number of gases are brought together in the form of tables for 13 gases, computed from formulations which include all available information. Data for the first temperature range in the case of the mixture N_2-CO_2 are also given. Viscosities and specific heats are also included in the tables, all for zero pressure.

2 Thermal Conductivities for Several Gases With a Description of New Means for Obtaining Data at Low Temperatures and Above 500°C, by F. G. Keyes, Massachusetts Institute of Technology, Oct. 1952, *MIT-1-M.*

Effort has been expended in three directions. First, apparatus for the temperature range 50 to 350 C has been used to obtain thermal conductivity measurements for argon, hydrogen, nitrous oxide, methane, and ammonia. Effect of pressure on conductivity of these gases was also obtained. Second, apparatus for low temperature measurements of gases and liquids was completed; and values of the dE/dt for copper-constantan obtained. Third, equipment for conductivities from 500 to 900 C has been brought to the stage of use for calibration of the platinum-10% rhodium thermocouples. Cell design has been executed, testing of the cell to discover its operating characteristics remains (as of Aug. 1952) to be carried out.

3 Thermal Conductivity of Gases, by F. G. Keyes, Massachusetts Institute of Technology, *Trans. ASME*, vol. 76, no. 5, pp. 809–816, 1954, *MIT-5-P.*

This paper is a continuation of earlier reported work in connection with two of the fundamental properties required for understanding and designing heat transfer equipment. New measurements of heat conductivity are presented along with values for viscosity obtained by correlation of all available data found in the literature. The simplest substance from the point of view of theory is the monatomic gas. The results of a study of the five rare gases are included.

4 Thermal Conductivity of Gases, by F. G. Keyes, Massachusetts Institute of Technology, *Trans. ASME*, Nov. 1955, *MIT-9-P.*

A paper presented before the Heat Transfer Division at the 1953 Annual Meeting contains a description of the below-ice-point temperature apparatus for measuring thermal conductivities of gases and liquids. A few results for neon were reported during the past year.

B Liquids

1 Thermodynamic and Transport Properties of Liquids, Problem I. Thermal Conductivities of Liquids, by E. F. Johnson, Jr., and W. J. Sheffy, Princeton University, Oct. 1951, *PR-17-M.*

The measurement of thermal conductivities and diffusivities in pure liquids and liquid mixtures over extensive pressure and temperature ranges is considered. On the basis of experimental work and a survey of the literature, a comparison is made between a thick disk-type apparatus and a heterogeneous apparatus of concentric metal cylinders for measuring thermal diffusivities in steady- and unsteady-state operation.

C Solids

1 Influence of Strain Rate on High Temperature Tensile Properties of Sheet Material, by G. J. Guarnieri and J. Miller, Cornell Aeronautical Laboratory, Jan. 1948, *CAL-11-M.*

Because of the dependence of high temperature tensile properties on the rate of strain, this variable has been included in the determination of the tensile characteristics of 25-20-2 Si stainless steel, regular Inconel, and S-816 sheet stock. It was shown that a 50 per cent change in tensile strength could be induced in these alloys by a tenfold change in strain rate.

Further analysis of the data on temperature, stress, strain, and time indicates that some insight into the high temperature deformation mechanism can be obtained, particularly if consideration is given to measurement of the activation energies involved. This viewpoint was used to explain the time or strain-rate effect on elastic limit at high temperature.

2 High Temperature Deformation Characteristics of Several Sheet Alloys, by J. Miller and G. J. Guarnieri, Cornell Aeronautical Laboratory, April 1948, *CAL-17-M.*

From constant rate tensile tests at elevated temperatures, true stress–true strain characteristics were determined for five different types of alloys over a range of temperatures and strain rates. The true stress–true strain plots are used to yield information on changes effected in properties of the alloys as they undergo high temperature plastic deformation.

An attempt was made to use the data to learn more about the mechanics of deformation at elevated temperatures through determination of activation energies associated with deformation. The increase in such energy values with decrease in stress, found for all materials tested, was attributed to the effect of elastic distortion on crystal lattice. A simplified mechanism of deformation is described using these characteristics, and the relationship of the flow process to metallic diffusion is pointed out.

3 Problems Encountered in a Study of the Beryllium-Chromium System, by G. H. Schippereit, Polytechnic Institute of Brooklyn, May 1948, *PIB-1-M.*

Attempts to produce alloys of the system proved unsuccessful. One difficulty encountered was the inability to find suitable crucibles; conventional melting atmospheres were unsatisfactory, and argon or a high vacuum was used, and, while beryllium could be obtained, chromium available contained a great deal of chromous oxide. Operational techniques and causes of their failures are discussed. A diffusion experiment showed that promising alloys do exist in this system. Experiments were discontinued when production of beryllia shapes was stopped by the supply house.

4 A Survey of Refractory Compounds and Metallic Binders, by R. H. Witt and O. H. Henry, Polytechnic Institute of Brooklyn, May 1948, *PIB-13-M.*

Study contains a review of the literature, experimentation on the wettability of various refractory metals on tungsten carbide, titanium carbide, and tantalum carbide, and development of a method to survey quickly the possible combinations of carbide metal.

Supplementary bibliography is appended covering papers published after the completion of this survey.

5 Changes in Martensite Structure as a Record of Temperature—Part I, by M. Stoll and G. H. Schippereit, Polytechnic Institute of Brooklyn, June 1948, *PIB-2-M.*

A method of determining temperatures, temperature distribution, and gradients of the metal constructions used in rocket and jet propulsion units has been proposed, and its theory and calibration are described. In this method, the metals themselves act as their own thermal indicators. By calibration of known temperature-responsive changes occurring in the microstructure, in the hardness, and in other physical properties, an indication of temperature at any one point is possible. In this initial research the tempering of martensite has been employed as the temperature indicator. The thermal changes have been checked by metallographic methods and hardness measurements.

6 Changes in Martensite Structure as a Record of Temperature—Part II, by G. H. Schippereit and O. H. Henry, Polytechnic Institute of Brooklyn, June 1948, *PIB-4-M.*

Describes several efforts to prove the feasibility of determining temperatures in combustion chambers by use of changes in martensite. In a final and successful experiment, a calibrated temperature-responsive steel venturi tube was fabricated and fired under controlled conditions of time and temperature. The temperatures encountered by the tube were approximately indicated by hardness measurements and microscopic examination. Results of the experiment reveal that temperature can be measured by the changes occurring in the tempering of martensite.

Photomicrographs and hardness curves of the results thus far obtained are included in this report.

7 Short-Time High Temperature Tensile Properties of Six Sheet Alloys, by James Miller and G. J. Guarnieri, Cornell Aeronautical Laboratory, *Amer. Soc. for Met., Trans.*, vol. 41, p. 167, Aug. 1948, *CAL-21-M-P.*

The short-time tensile properties at elevated temperatures and various strain rates are presented for six available sheet materials. The application and utility of such data are noted together with their limitations from the standpoint of structural design and materials evaluation.

8 The Effect of Sigma Phase on the Short Time High Temperature Properties of 25 Chromium–20 Nickel Stainless Steel, by G. J. Guarnieri, J. Miller, and F. J. Vawter, Cornell Aeronautical Laboratory, *Amer. Soc. for Met., Trans.*, vol. 42, p. 981, May 1949, *CAL-26-M-P.*

Using a 25 Cr–20 Ni stainless steel with 2 Si, correlation of high temperature tensile and creep properties (up to 100 hr duration) was made with the type and pattern of distribution of sigma constituent. Three sigmatized microstructures were prepared, an acicular pattern, a medium sigma size well distributed, and a finely distributed sigma. Two fully austenitic structures of different grain size were also tested to isolate effect of austenitic grain size on high temperature properties studied.

While the hard sigma phase constituent increased materially the tensile and yield strength properties of the chromium-nickel steel up to temperatures of approximately 1400 F (760 C), a corresponding decrease in long-time creep strength properties occurred. This loss in creep strength under slow strain rate conditions was more pronounced with more finely distributed sigma microstructures. Finely divided type of sigma structure was found desirable from the standpoint of minimizing room temperature embrittlement as indicated by bend tests.

9 Short Time High Temperature Bending Fatigue Properties of Sheet Materials, by F. J. Gillig, Cornell Aeronautical Laboratory, Sept. 1949, *CAL-30-M*.

Qualitative short time high temperature fatigue studies were made for three heat resistant alloys. The complexity of the mechanism of high temperature fatigue failure was established. The investigation brought out the limitations of the constant deflection type fatigue machines for high temperature work. A number of problems are proposed for further investigation.

10 Record of Conference on Fatigue of Metals at High Temperatures, by P. K. Porter and H. J. Yearian, Cornell Aeronautical Laboratory, May 1950, *CAL-60-R*.

Papers as follows:

Dolan, T. J.
Past Work on the Fatigue of Metals in the High Temperature Field

Freudenthal, A. M.
Current Theories of Fatigue

Fuller, F. B.
Elevated Temperature Fatigue Testing at Air Material Command

Olcott, E. L., and Promisel, N. E.
High Temperature Fatigue Program of the Bureau of Aeronautics

Grant, N. J.
Strain Rate Aspects of Fatigue Testing

Jones, W. E., and Wilkes, G. B.
Effect of Notches and Shot Peening on High Temperature Fatigue Properties

Smith, L. W.
High Temperature Fatigue Program at C.A.L.

Lazan, B. J.
Creep and Rupture Properties of Temperature Resistant Materials under Unidirectional and Reversed Fatigue Stress

Crows, H. C., and Simmons, W. F.
Some High Temperature Tensile-Fatigue Data on Gas Turbine Alloys

11 The Effect of Rapid Heating on the Specific Heat Curve of Low Carbon Steel at the Phase Transformation Points, by A. M. Nathan, New York University, March 1951, *NYU-6-M-P*. (See also letter to the Editor, *J. Appl. Phys.*, vol. 22, no. 2, pp. 234–235, Feb. 1951.)

A dynamic method of measuring the specific heat curves of metals under conditions of rapidly increasing temperature (1000 C per sec) is described and some results obtained with it are given. The method is used for a preliminary study of the specific heat curves of low carbon steel at the phase transformation points. The specimen is heated in a vacuum by high amperage d-c currents. During the heating, the temperature of the steel and the power input are continuously recorded. These quantities are recorded by photographing the face of a cathode-ray tube which displays them. Results obtained indicate that the peak of specific heat which normally occurs at the A_1 allotropic phase transformation point under equilibrium conditions is greatly affected by rapid heating, while the specific heat anomaly at the curie point is not affected by the rate of heating.

12 Formation of Oxide Film on Chromium Steels, by H. J. Yearian, Purdue University; paper presented at the Annual Meeting of the American Physical Society, Feb. 1951, *PUR-15-P*.

Electron micrographs of the surface of chromium steels taken after increasing periods of oxidation at temperatures of 500 to 700 C show that a uniform film of small crystallites is quickly formed; most of the growth thereafter is confined to small localized regions. These regions of local attack form at random positions on the metal surface, grow rapidly at first, then more slowly in the form of nodules; new growth centers are formed continuously. As oxidation proceeds, the local growths gradually coalesce to form a continuous scale which may be removed mechanically, leaving a quite uniform oxide film. The density and rate of growth of the nodules increase with increase of time and temperature of oxidation and with decrease of the chromium content of the alloy; x-ray diffraction shows that Fe_2O_3 is the principal component of the nodules, whereas transmission electron diffraction (of stripped films) indicates a high proportion of Cr_2O_3 in the thin film substrata. Experiments to determine the cause of the localized attack will be described.

13 Cyclic Loading Effects on the Creep Properties of Sheet Materials, by F. J. Gillig and G. F. Guarnieri, Cornell Aeronautical Laboratory, Sept. 1951, *CAL-38-M*.

Armco iron and commercial aluminum were used to establish generalizations concerning the variables, amplitude of cyclic load between 0 and 50 per cent of the mean stress, temperature, and frequency of load variation from 1.5 to 4200 cpm.

Data show superposition of a cyclic load upon a static tensile load in a creep test on Armco iron will not necessarily cause deformation to proceed at an increased rate, provided the frequency is high enough for the conditions of stress and temperature which prevail. Only a limited amount of data was obtained for the aluminum prior to termination of the project.

14 Limiting High Temperature Creep and Rupture Stresses of Sheet Alloys for Jet Applications, by G. J. Guarnieri and J. Salvaggi, Cornell Aeronautical Laboratory, Sept. 1951, *CAL-39-M*.

High temperature creep and fracture stresses have been determined for 24 alloys in sheet form over the range of service temperatures and times of interest to designers of jet aircraft parts. Included are steels representative of the low alloy ferritic and austenitic stainless types, cobalt base alloys, Inconel X, 24S-T3 alclad aluminum, and FS-1H magnesium. While the data presented were obtained from a single heat for each material, they provide a design basis for efficient utilization of sheet alloys in high temperature service.

15 Lattice Parameters of the $FeFe_{(2-x)}Cr_xO_4$ Spinel System, by H. J. Yearian, J. M. Kortright, and R. H. Langenheim, Purdue University, *J. Chem. Phys.*, vol. 22, no. 7, pp. 1196–1198, July 1954, *PUR-26-P*.

Spinels of the $FeFe_{(2-x)}Cr_xO_4$, $0<x<2$, system have been made by reduction of the corresponding sesquioxide solid solution at 1180, 1100, and 950 C and the lattice parameters determined at room temperature. The solutions of approximately stoichiometric composition have lattice parameters which vary with x in a nonlinear manner from $8.396 \pm 0.002A$ at $x = 0$ to $0.376 \pm 0.002A$ at $x = 2$. The four essentially linear segments comprising the total curve are interpreted as follows: from $x = 0$ to $x = 0.3$ the structure is completely inversed; from $x = 1.28$ to $x = 2.0$ it is completely normal; between these regions reversion from the inversed to the normal form occurs in two successive stages. Oxygen rich spinels crystallized at 950 C show the same general variations of parameter but the region of complete inversion extends to approximately $x = 0.6$.

II Physical Processes

A Heat Transfer

1 A Theoretical Investigation of the Temperature Field in the Laminar Boundary Layer on a Porous Flat Plate With Fluid Injection, by S. W. Yuan, Polytechnic Institute of Brooklyn, Sept. 1947, *PIB-11-R*.

A theoretical investigation of the flow of hot fluid over a porous flat plate under the condition of uniform fluid injection from the bottom of the plate was made. The momentum equation and the corresponding energy equation for the boundary layer were set up with the velocity of injection assumed to be uniformly distributed along the plate.

In the solutions of the laminar boundary layer equation, the momentum and energy equations were reduced to the integral relation form similar to the Kármán integral relation of the Prandtl equation. The velocity and temperature profiles were assumed as a polynomial of the fourth degree and also as an exponential function.

Solution of the above equations gave the relationship of length in the direction of flow to the boundary layer thickness and to the temperature layer thickness in the boundary layer. The velocity profiles and the temperature profiles for different Prandtl numbers were then calculated. The solution was also extended to the case where the coolant injection begins at any distance from the leading edge of the plate.

The relation between the wall temperature and the rate of coolant injection was calculated for different Reynolds numbers, Prandtl numbers, and for a partially extended porous plate. The relations are shown in curves which accompany the article.

2 Heat Transfer in a Laminar Boundary Layer on a Partially Sweat-Cooled Plate, by Shao Wen Yuan and C. Chin, Polytechnic Institute of Brooklyn, Aug. 1949, *PIB-19-R*.

A theoretical investigation is made of the flow of a hot fluid over a partially porous flat plate under the condition of uniform injection from the bottom of the plate. An expression for the boundary layer thickness at the beginning of the porous portion is derived and used to determine the variation of boundary layer thickness in the direction of flow.

The relation between wall temperature and the rate of coolant injection is calculated for different values of x_i where x_i is the distance measured from the leading edge of the plate to the point at which fluid injection begins. The results are shown in accompanying curves.

3 Heat Transfer in a Laminar Compressible Boundary Layer on a Porous Flat Plate With Fluid Injection by S. W. Yuan, Polytechnic Institute of Brooklyn, *J. Aero Sci.*, vol. 16, no. 12, pp. 741–748, Dec. 1949, *PIB-10-M-P*.

A theoretical investigation was made of flow of hot fluid over a porous flat plate under

the condition of uniform fluid injection from the bottom of the plate. Kármán integral relation of the momentum equation was derived with the uniform velocity of injection taken into consideration. The velocity profile was assumed as a polynomial of the fourth degree.

Solution of the above equation gave the relationship of length in the direction of flow to the boundary layer thickness. The velocity profiles and the temperature profiles were calculated then for a Prandtl number equal to unity.

The relation between wall temperature and the rate of coolant injection was calculated for different Mach numbers, Reynolds numbers, and viscosity variation with temperature.

4 Further Investigation of Heat Transfer in a Laminar Compressible, Boundary Layer on a Porous Flat Plate With Fluid Injection, by Shao Wen Yuan and D. E. Whitford, Polytechnic Institute of Brooklyn, Dec. 1949, *PIB-20-R.*

Theoretical investigation made of the flow of hot fluid over a porous flat plate under the condition of uniform fluid injection from the bottom of the plate. It was assumed that the fluid density varies inversely as a certain quartic function of the distance inside the boundary layer, and that the viscosity of the fluid varies directly as one-half power of the same function.

In the solution of the integral relation of the momentum equation, a process similar to that employed in *PIB-10-M-P* is carried out. The results show that the mass coolant needed to cool the wall to a predesignated temperature in the present case is 10 per cent less than that which is indicated in the previous case, given in *PIB-10-M-P.*

5 Heat Transfer in a Laminar Compressible Boundary Layer on a Porous Flat Plate With Variable Fluid Injection, by S. W. Yuan and N. Ness, Polytechnic Institute of Brooklyn, Sept. 1950, *PIB-15-M.*

A theoretical investigation of the heat transfer in a laminar compressible boundary layer on a partially porous flat plate with variable fluid injection (trapezoidal and bilinear types) is made. The method of iteration and graphical integration is used to obtain the solution of the boundary layer equation.

The relation between wall temperature and the rate of coolant injection is calculated for three different injection profiles (trapezoidal, bilinear, and uniform). The results indicate that for equal quantities of coolant injected, the variable injection cases are slightly more efficient than is the uniform injection case.

6 Heat Conduction in Simple Metals, by M. L. Storm, New York University, *J. Appl. Phys.*, vol. 22, no. 7, pp. 940–951, July 1951, *NYU-22-P.*

The partial differential equation of heat conduction is a nonlinear equation when the temperature dependence of the thermal parameters (i.e., the thermal conductivity, K, the product of the density, and the specific heat constant pressure S) is taken into account. It is shown that a mathematical condition for the transformation to linear form of the one-dimensional, nonlinear, partial differential equation of heat conduction is the constancy of $1/(KS)\ [(d/dT)\log(S/K)]^{1/2}$.

This discovery is the motivation for an investigation of the relations between the thermal parameters of simple metals on the basis of the theory of solids and available experimental data. It is found that KS is essentially constant, its variation with temperature being much less than that of either K or S considered separately. It is also shown, as a result, that the condition for the afore-mentioned transformation is valid for simple metals. Application of the transformed equation to the solution of problems in heat conduction is considered.

7 Experimental Investigation of the Isothermal Laminar Boundary Layer on a Porous Flat Plate, by P. A. Libby, L. Kaufman, and R. P. Harrington, Polytechnic Institute of Brooklyn, *J. Aero. Sci.*, vol. 19, no. 2, pp. 127–135, Feb. 1952, *PIB-16-M-P.*

The transition Reynolds numbers and velocity profiles of the laminar isothermal boundary layer on a porous flat plate with suction or injection have been measured and compared with the laminar boundary layer analyses that have been carried out in the past several years. The results indicate that porous plates closely approximating the mathematical or ideal porous plates can be realized and that the theoretical velocity profiles are in good agreement with experiment.

8 Heat Insulating Properties of the Laminar Compressible Boundary Layer, by P. A. Libby, Polytechnic Institute of Brooklyn, July 1952, *PIB-23-P.* Presented at the Eight International Congress on Theoretical and Applied Mechanics, Istanbul, 1953.

Results of a theoretical investigation of the insulating properties of a laminar compressible boundary layer are given. The Kármán-Pohlhausen integral method extended to both the momentum and energy partial differential equations of the boundary layer has been used with a fourth degree polynomial for the velocity profile and a fifth degree polynomial in the stagnation enthalpy profile. The resulting two integral differential equations are then solved for two unknown functions of the distance along the wall. These two functions are related to the boundary layer thickness and to the wall temperature. Initial conditions corresponding to a given initial wall temperature and an initial boundary layer thickness are prescribed. Exact, closed-form solutions for the case of zero axial pressure gradient are obtained. For the case with axial pressure gradient, approximate numerical solutions for the interesting case of an accelerating pressure gradient have been obtained. Circumstances under which the laminar compressible boundary layer may insulate a surface from high energy gases are discussed.

9 Heat Transfer over a Sweat-Cooled Surface in Laminar Compressible Flow With a Pressure Gradient, by M. Morduchow, Polytechnic Institute of Brooklyn, *J. Aero. Sci.*, vol. 19, no. 10, pp. 705–712, Oct. 1952, *PIB-21-P.*

A simple expression is derived for the normal injection velocity distribution theoretically required to maintain a given uniform temperature along a porous surface in the laminar boundary layer region of a compressible flow with a given velocity distribution outside of the boundary layer. This expression is valid for any given free stream Mach number but is based on a Prandtl number of unity and on the assumption that the viscosity coefficient varies linearly with the temperature. By using the Dorodnitsyn type of transformation, the variation of fluid properties even in the case of zero Mach number is taken into account. This study is of particular practical interest in connection with the sweat-cooling of turbine blades and of airfoil surfaces in high speed flow. The method of analysis consists of applying the Kármán-Pohlhausen method to both the momentum and energy boundary layer equations and of using an additional heat balance equation involving the coolant temperature. A closed-form approximate solution of the equations is then derived. Numerical examples for flow in the immediate vicinity of a stagnation point and for a typical type of flow over a turbine blade are given.

10 Three-Dimensional Liquid Analog for the Determination of Temperature Distribution, by G. A. Sterbutzel and J. L. Beal, Cornell Aeronautical Laboratory, Oct. 1952, *CAL-44-M.*

The development and use of a three-dimensional analog for the determination of steady-state temperature patterns in a structure are described. The particular analog model was used to investigate temperatures in a rocket motor whose wall was cooled by a liquid flowing in ducts surrounding the combustion chamber.

11 On the Temperature Distribution Along a Semi-Infinite Sweat-Cooled Plate, by Nathan Ness, Polytechnic Institute of Brooklyn, *J. Aero. Sci.*, vol. 19, no. 11, pp. 769–768, Nov. 1952, *PIB-22-P.*

A theoretical investigation of the temperature distribution along a semi-infinite porous flat plate under the condition of uniform injection from the bottom of the plate is made.

A heat balance differential equation of the second order, including a term containing the physical parameters of the plate, is derived and employed in conjunction with Prandtl boundary layer equations of continuity, momentum, and energy for a solution of the problem.

The temperature distribution along the plate is obtained for the cases of thermal conductivity not equal to, and equal to, zero. Results show that the inclusion of the thermal conductivity term in the heat balance equation eliminates the infinite temperature gradients at the leading edge.

Other results when thermal conductivity is considered are: (a) The boundary conditions at the leading edge (i.e., the ratio of wall to free stream temperature and the axial temperature gradient there) may not be chosen arbitrarily but are related mathematically to each other; (b) the ratio of thermal to velocity boundary layer thickness is less than unity at the leading edge for Prandtl numbers greater than 0.35 and is equal to unity at an infinite distance downstream; and (c) at an infinite distance downstream, the wall temperature approaches the coolant temperature.

12 Heat Transfer Coefficients for Gases: Effect of Temperature Level and Radiation, by H. J. Ramey, J. B. Henderson, and J. M. Smith, Purdue University; Heat Transfer Symposium, American Institute of Chemical Engineers, Prepr. 10, Dec. 1953, *PUR-24-P.*

Convection heat transfer coefficients for the cooling of steam and air flowing inside a 2-in. pipe were measured from 500 to 1200 F at gas-to-wall temperature differentials of 300 to 1000 F, and over a range of Reynolds numbers from 2000 to 20,000 for air and 5000 to 60,000 for steam.

The convection heat transfer coefficients for air increased slowly with temperature level. Similar measurements with steam indicated that published information of the emissivity of steam were satisfactory for predicting radiation contributions encountered within the above range of variables.

Data taken with different entrance conditions indicated that the convection coefficients could be increased several hundred per cent at constant Reynolds number by substituting a jet entry for the usual straight entrance section with well-developed turbulence.

13 A Method for Analyzing the Heat Insulating Properties of the Laminar Compressible Boundary Layer, by P. A. Libby and A. Pallone, Polytechnic Institute of Brooklyn, *J. Aero. Sci.*, vol. 21, no. 12, Dec. 1954, *PIB-24-P.*

A method for investigating the insulating properties of a laminar compressible bound-

ary layer on a two-dimensional surface with zero heat transfer is presented.

The Kármán integral method extended to both the momentum and energy partial differential equations of the boundary layer has been used. Thus the velocity and stagnation enthalpy profiles have both been taken as sixth degree polynomials. The two resulting integral differential equations are then solved for two unknown functions of the distance along the wall. These two functions are related to the boundary layer thickness and to the wall temperature. Initial conditions corresponding to a given initial wall temperature and an initial boundary layer thickness are prescribed. Exact closed-form solutions for the case of zero axial pressure gradient are obtained. For flows with significant pressure gradients, numerical solutions are required in general. Several numerical examples of practical interest are presented.

14 A Provisional Analysis of Turbulent Boundary Layers with Injection, by J. H. Clarke, H. R. Menkes, and P. A. Libby, Polytechnic Institute of Brooklyn, *J. Aero Sci.*, vol. 22, no. 4, April 1955, *PIB-26-P.*

Prandtl's analysis of the incompressible turbulent boundary layer over a flat plate is extended in this report to include the effect of uniform transverse fluid injection. The nondimensional parameters characterizing such a flow are deduced by dimensional reasoning. A velocity profile is generated by considering the flow over a plane wall; this distribution reduces to the universal log law when the mass transfer is zero. The expression also serves to relate the local skin friction to the boundary layer thickness. When these relationships are used in conjunction with the Kármán integral, the problem becomes mathematically specified.

15 Prandtl Number Determination by Means of Recovery Factor Measurements, by R. A. Seban, S. Scesa and A. Levy, University of California at Berkeley, Sept. 1954, *UCB-1-R.*

A cylindrical probe was used to measure the differences between stagnation and wall temperatures. Recovery factors were obtained for the laminar boundary layer flow of air, N, He, and He-N mixtures in the 100 to 600 F range. The Prandtl number was inferred from the recovery factor results in which the square of the measured recovery factor was within 3 per cent of the available values of the Prandtl number for air and N and within 1 per cent when corrected for theoretically evaluated errors; these are magnitudes of uncertainity comparable to that on the individual properties from which the Prandtl number is evaluated. The less decisive results obtained with He and He-N mixtures indicated the available Prandtl number values for He may be too high.

16 Laminar Pipe Flow with Injection and Suction Through a Porous Wall, by S. W. Yuan; presented at the Heat Transfer and Fluid Mechanics Institute, June 1955, Polytechnic Institute of Brooklyn, *PIB-25-P.*

The effect of injection and suction at the wall on the two-dimensional steady-state laminar flow of a fluid in a porous wall pipe is investigated by the solution of the Navier-Stokes equations in cylindrical coordinates. A solution of the dynamic equations, reduced to a third-order nonlinear differential equation, is obtained; a perturbation method is used to solve the equation for flows through the wall. Velocity components are expressed as functions of the ratio of velocity through the wall to the maximum axial velocity at the entrance, the coordinates of the pipe, and the properties of the fluid. Injection at the wall of the pipe increases the friction coefficient at the wall. For an injection ratio $Q/W = 0.01(500 \leq R_x \leq 2500)$, the coefficient is increased by 70 to 85 per cent over the zero injection case (Poiseuille case).

17 Supplementary Information on Prandtl Number Determination by Means of Recovery Factor Measurements, by R. A. Seban and A. Levy, University of California at Berkeley, Nov. 1955, *UCB-2-R.*

Additional measurements made with air in the 500 to 700 F range indicate that the magnitude of the square of the apparent recovery factor remains the same to 675 F. The source of the error in the platinum probes is unresolved, but it appears to be associated with the presence of oxygen in the gas, since the anomalous behavior was not experienced when operating with nitrogen at temperatures up to 625 F. Results of measurements with Bakelite probes were about the same as the results previously obtained with platinum probes for air and helium in the 100 to 200 F range.

18 Heat Transfer of a Laminar Pipe Flow with Coolant Injection, by S. W. Yuan and A. B. Finkelstein, Polytechnic Institute of Brooklyn, submitted at the Heat Transfer and Fluid Mechanics Meeting, June 1956, *PIB-27-P.*

The effect of coolant injection at the wall on the temperature distribution of the laminar flow of a fluid in a porous wall pipe was investigated. The temperature distributions in the pipe for various fluid injections were obtained by solving the energy equation. The heat transfer coefficient at the wall was shown to decrease with an increase in the rate of coolant injection, whereas it was previously found that the friction coefficient at the wall increases with an increase of fluid injection. Thus analogy between the heat transfer and momentum transfer does not exist in porous wall cooling of pipe flow.

B Mass Transfer and Mixing

1 Theoretical and Experimental Investigations of the Mixing of a Supersonic Stream with an Induced Secondary Stream as Applied to Ducted Propulsive Devices, by H. L. Pool and J. V. Charyk, Princeton University, Sept. 1950, *PR-42-R.*

Test results on certain aspects of ejector performance are reported including effects of such factors as primary to secondary jet area ratio, location of actuating jet, under- and overexpansion of supersonic primary jet nozzle, etc. Some typical test data are also included for the case in which chemical reaction occurs between the two fluid streams. Pressure and temperature distributions along the duct are included.

An appendix treats the problem of constant area or constant pressure mixing according to the usual one-dimensional fashion. Appropriate selection of parameters permits a solution in very simple form.

2 Mixing and Burning of Two Concentric Fluid Streams, by J. V. Charyk, I. Glassman, and R. R. John, Princeton University, Fourth Symposium (International) on Combustion; Williams and Wilkins, Baltimore, pp. 886–893, 1953, *PR-39-P.*

Report includes an experimental verification of the use of the one-dimensional equations of mixing and burning in the theoretical performance calculations for a liquid oxygen-gasoline-air ducted rocket. Methods are presented for predicting empirically the longitudinal static pressure distribution in the ducted rocket burner and thus the burner length as a function of R and R^* for the liquid oxygen-gasoline system. These results are generalized, making it possible to predict empirically the static pressure distributions along the burner duct for a wide range of ram-rocket operating conditions, including other propellants and different flight conditions.

3 SQUID Conference on Atomization, Sprays, and Droplets, Northwestern University, Sept. 1953, Feb. 1955, *NTI-1-C.*

A summary is presented of the proceedings of the conference. The following four papers are presented in their entirety:

Pilcher, J. Mason
Characteristics of Sprays and Droplets

Thomas, R. E.
Drop-Size Distributions and Their Averages

Graves, C. C., and Bahr, D. W.
Review of Mass and Energy Transfer Between Liquid Droplets and Surrounding Gases

Samaras, D. G.
Injection in Afterburning Turbojets

Abstracts are given for, or references are made to, the following thirteen papers:

Marshall, W. R., Jr.
Review of Experiments and Empirical Correlations Relating the Production of Sprays

Laster, R., and Doumas, M.
Review of Theoretical and Mathematical Analyses of the Performance of Atomizing Nozzles

Bahr, D. W.
Fuel Spray Spreading and Evaporation in a Flowing Air Stream

York, J. L.
Review Instrumentation and Methods of Experimental Study

Bolt, J. A.
An Apparatus for Suspending Small Droplets of Liquid in Space

Comings, E. W.
Measurement of Dry Bulb Temperature in Mists

Johnson, H. F., Feild, R. B., and Tassler, M.C.
Gas Absorption and Aerosol Collection in a Venturi Atomizer

Fremont, H. A.
Fuel Injection Problems in Turbojets

Longwell, J. P.
Fuel Injection Problems in Ramjets

Miesse, C. C.
Application of Spray Technology to Liquid Propellant Rockets

Meyers, P. S., Uyehara, O. A., and El Wakil, M. M.
Vaporization of Fuel Droplets in a Diesel Engine

Meyers, W. E.
Fuel Injection Problems in Otto Cycle Engines

Johnstone, H. F., Marshall, W. R., York, J. L., Comings, E. W., and Lamb, G. G.
Chemical Engineering Applications

4 A New Technique for Drop-Size Distribution Determinations, by A. P. R. Choudhury and W. F. Stevens, Northwestern University, submitted to the American Institute of Chemical Engineers, Aug. 1955, *NTI-2-M.*

A simple, rapid method for determining the drop size distribution of a liquid spray is described which involves the capture and instantaneous freezing of the entire spray in a liquid nitrogen bath, followed by screening of the resulting solid spheres into sized fractions. No complex sampling or counting procedures are required. The procedure is described in detail, and advantages and disadvantages of the method are given. Typical drop size distribution curves obtained by the method are included.

5 A Literature Survey on Some Physical Aspects of the Combustion of Falling Fuel Drops, by P. M. Blair, Purdue University, Nov. 1955, *PUR-27-R.*

Dynamics of falling drops: The dynamics of rigid spheres are reviewed, and

available terminal velocity and drag coefficient data are given for liquid drops falling in 70 F air. Factors determining the size and shape of stable falling drops are discussed.

Heat transfer for drops and spheres: Summaries are given of theoretical analyses which have been reported on (a) heat transfer to a sphere immersed in flowing fluid in the absence of mass transfer, and (b) heat transfer to a hypothetical spherical fuel drop burning in still air and surrounded by a concentric flame front.

Mass transfer for drops and spheres: The laws for molecular and eddy diffusion are given for mass transfer in the absence of heat transfer, and experimental results showing the effect of relative air velocity on such mass transfer coefficients are summarized.

6 Composition Change in Binary Component Spray Vaporization at Atmospheric Pressure, by J. F. Culverwell, P. W. Grounds, Jr., G. G. Lamb, and W. F. Stevens, Northwestern Technological Institute, submitted to the American Institute of Chemical Engineers, March 1956, *NTI-3-P*.

The behavior of the *o*-dichlorobenzene-tetrachloroethylene system was studied in air from 400 to 1000 F for an investigation of the factors effecting a change in composition with vaporization of the binary component spray. Calculations agreed with experimental data during the first 5 in. of nozzle-to-tray travel. Equations are presented which describe mathematically the vaporization process with the assumption of liquid diffusion control. Results indicated that the variation of residual spray composition with vaporization is a function of initial composition, chamber air temperature, and nozzle characteristics. Feed temperature and pressure and nozzle-to-tray distance locate the position on a vaporization-composition curve but do not affect its shape.

C Fluid Flow

1 On the Possibility of Representing One-Dimensional Gas Motion by Means of an Electrical Analogy, by J. G. Logan, Cornell Aeronautical Laboratory, June 1947, *CAL-2-M-R*.

The possibility of representing the motion of a gas in a half-open pipe by means of a loss-free transmission line is considered. The one-dimensional wave equation is linearized by considering the wave velocity constant during a small time interval. The wave equation is then related to the transmission line equation. Because of the difficulties involved in test procedure, the use of such an analogy appears to be of little value.

2 Study of Gas Oscillations in Half-Open Pipes of Various Shapes, by G. Rudinger and J. G. Logan, Cornell Aeronautical Laboratory, June 1947, *CAL-4-M-R*.

The influence of shape of a half-open pipe on gas oscillations is investigated. The mathematical treatment used is a continuation of a method developed by H. Levy. The effect of shape is evaluated by two parameters. One shows the influence of the acoustic resonance frequency and the other determines how the effect of the maximum amplitude of oscillations is modified by shape. Analytical relations have been derived for a number of configurations.

The conclusions reached are of a preliminary nature pending experimental verification.

3 Two-Dimensional Supersonic Wind Tunnel Simulation of the Flow Over the External Surface of Ducted Bodies With and Without Spillover, by M. Kamrass, Cornell Aeronautical Laboratory, June 1947, *CAL-5-M*.

A series of tests of wedge airfoils was made in the CAL supersonic wind tunnel at a Mach number of 1.72. The object of the tests was a two-dimensional simulation of the condition of spillover on the forward end of ducted bodies and a study of the effect of spillover on the external wave drag of such bodies. Four leading edges of varying thicknesses were tested. Results show that as edge thickness increases, the pressure coefficient decreases in a region near the nose, but increases behind this region. Schlieren observations reveal the presence of a region of expansion following the detached shock in front of the blunt nose. This expansion culminates in a second shock a short distance aft to the nose.

4 Two-Dimensional Supersonic Wind Tunnel Investigations of Flow in a Duct With Fluctuating Exit Pressure, by M. Kamrass, Cornell Aeronautical Laboratory, June 1947, *CAL-7-M*.

A wind tunnel investigation of diffusers with controlled periodically varying back pressures was initiated, in an attempt to determine the effects of frequency and amplitude of such pressure fluctuations upon the instantaneous shock pattern and the range of travel of the normal shock inside the diffuser. This report describes the experimental technique used.

5 Remarks on the Interaction Between Shock Waves and Boundary Layer in a Transonic and Supersonic Flow, by L. Lees, Princeton University, Nov. 1947, *PR-1-M*.

Purpose of the report is to explore a possible explanation of phenomena observed when a shock wave incident upon a surface interacts with the boundary layer at the surface.

It is concluded that the interaction between a shock wave and a laminar boundary layer observed by Liepmann and Ackeret depends critically on boundary layer thickness. Influence of Reynolds number and Mach number on the interaction is also investigated. Some conclusions reached are applied to the interaction between the boundary layer and an oblique shock generated by supersonic flow "in a corner."

The fundamental differences between the normal Prandtl subsonic boundary layer and a boundary layer interacting with an "external" supersonic flow are discussed briefly with the aid of the equations of motion.

6 Unsteady One-Dimensional Flows With Heat Addition or Entropy Gradients, by A. Kahane and L. Lees, Princeton University, *J. Aero. Sci.*, vol. 15, no. 11, pp. 665–670, Nov. 1947, *PR-2-M*.

Nonlinear differential equations of the Riemann type are derived for the solution of problems involving the propagation of one-dimensional waves in flows in tubes of slowly varying cross section with heat addition or entropy variation. Method of solution of these equations is described in an appendix. Transient flows arising when heat is added to a section (as in a combustion chamber) of an initially isentropic flow in a tube have been calculated. These results afford an insight into gas dynamic aspects of intermittent heat addition in a flowing gas and the apparently anomalous behavior at sonic velocity of steady gas flows with heat addition. The equations derived are well suited to the calculation of the nonlinear pulsejet cycle with heat addition, once a suitable model of combustion has been selected.

7 Investigation of Acoustic Jets, Part I, by G. Rudinger, J. Logan, and W. Dashifsky, Cornell Aeronautical Laboratory, Feb. 1948, *CAL-13-M*.

Preliminary studies of a small "acoustic jet" driven by the membrane of a loudspeaker indicate the possibility of extremely high specific impulses for this type of propulsion device. Photographs of the flow pattern indicate that one characteristic of the jet formation is the vortex flow pattern at the tube exit.

8 The Construction of Wave Diagrams for the Study of One-Dimensional Non-Steady Gas Flow, by G. Rudinger and L. D. Rinaldi, Cornell Aeronautical Laboratory, March 1948, *CAL-14-M*. (See also: "Wave Diagrams for Nonsteady Flow in Ducts," by G. Rudinger, D. Van Nostrand Co., 1955.)

This paper is an introduction to the method of characteristics for solving problems of one-dimensional, nonsteady gas flow. By following Riemann's approach, it can be shown that wave elements propagate along certain lines which are identical with characteristics lines. Construction of these lines in the position-time plane gives a clear picture of the motion of waves in ducts. Several new techniques for obtaining solutions of special problems are suggested.

9 The Flow at the Rear of a Two-Dimensional Supersonic Airfoil, by A. Kahane and L. Lees, Princeton University, *J. Aero. Sci.*, vol. 15, no. 3, pp. 167–170, March 1948, *PR-22-P*.

The flow at the rear of a two-dimensional airfoil moving at supersonic speed is of interest from a stability standpoint since the tail surfaces are likely to be influenced by this flow field.

The flow angle immediately behind the trailing edge of a flat plate airfoil and an airfoil with thickness has been calculated herein on the basis of oblique shock and Prandtl-Meyer wave theory. The deflection angle of the flat plate airfoil at a given Mach number is shown to first order to vary as the fourth power of the angle of attack. The magnitude of the flow deflection between Mach numbers of 1.2 to 5.0 is extremely small, being always less than 0.06 deg for an angle of attack of 0.1 radian (5.73 deg).

The mechanism of the return of the flow downstream of the airfoil to the free-stream direction is also discussed. The problem of the flow deflection immediately rearward of the two-dimensional supersonic airfoil has been previously treated in R. & M. No. 1930 by M. J. Lighthill; the results of that paper, however, appear to be in error.

10 Investigation of Acoustic Jets, Part II, by G. Rudinger, J. Logan, Jr., and O. B. Finamore, Cornell Aeronautical Laboratory, April 1948, *CAL-18-M*.

The experiments with an "acoustic" jet operated by a mechanical piston are described. High values of specific impulse, similar to those found previously for "acoustic" jets operated by a loudspeaker, were obtained. Maximum thrust was obtained at tube resonance frequencies. Visual observation of the flow patterns indicated that a vortex flow pattern was established at the exit of a straight tube when a jet was formed.

11 Preliminary Investigation of an Underwater Jet, by G. Rudinger, J. Logan, Jr., and O. B. Finamore, Cornell Aeronautical Laboratory, April 1948, *CAL-19-M*.

Preliminary studies of a small underwater jet driven by a mechanical piston indicate the possibility of extremely large specific impulse values for this type of propulsion device. Strong jet formation was observed at definite piston frequencies although these frequencies were much lower than resonance frequency values computed on the basis of the propagation of sound in water. Studies of the flow pattern established during jet formation indicate that a characteristic feature is the creation of vortex rings similar to those observed in "acoustic" jet investigations.

12 Flow in Ejectors Driven by Supersonic Jets, by K. D. Miller, Jr., Princeton University, May 1948, *PR-3-M*.

Equations for compressible flow in a gas

ejector are presented and solved, subject to the limitations of complete mixing and of frictionless flow. Form of solution was devised specifically for an ejector pumping air through the action of the exhaust jet of a rocket motor, but was kept general enough so that it would be readily applicable to other gas induction problems involving a supersonic jet. Appendix illustrates application to other problems. Numerical solutions of several cases were made and the results are included with a discussion of the effects to be expected with a variation in the essential parameters involved.

13 Stability of the Laminar Boundary Layer with Injection of Cool Gas at the Wall, by L. Lees, Princeton University, May 1948, *PR-40-R.*

The minimum critical Reynolds number, or "stability limit" for the laminar boundary flow of a hot gas over a porous-cooled flat plate is calculated as a function of the rate of coolant injection from the computed velocity and temperature distributions across the boundary layer. For low rates of coolant injection the stabilizing effect of the heat transfer at the wall is dominant, and the laminar flow is actually more stable than the isothermal Blasius flow over a nonporous flat plate. For large injection rates the minimum critical Reynolds number declines extremely rapidly and the flow is thought turbulent.

Results of the stability analysis suggest the possibility that laminar flow can be maintained for low rates of coolant injection, provided the porous section begins soon enough so that transition to turbulent flow does not occur before the porous section is reached. Wall temperatures at low rates of coolant injection necessary for laminar stability compare favorably with the wall temperatures for the turbulent boundary layer obtained with much higher injection rates.

14 A Water Analogue of the Isentropic Flow of Compressible Gases Which Have Arbitrary Ratios of Specific Heats, by R. F. Probstein and G. E. Hudson, New York University, Aug. 1948, *NYU-20-R.*

Experimental and theoretical studies on hydrodynamic analogs of compressible flow are described. It is shown that a channel with V-shaped cross section gives valid results for sound wave velcoity in a gas having a specific heat ratio of 1.5. Conventional water channels of rectangular cross section relate to gases with a specific heat ratio of 2.0.

15 The Construction of Wave Diagrams to Study the Propagation of Flame Fronts in Ducts, by G. Rudinger and L. D. Rinaldi, Cornell Aeronautical Laboratory, Nov. 1948, *CAL-23-M.* (See also: "Wave Diagrams for Nonsteady Flow in Ducts," by G. Rudinger, D. Van Nostrand Co., 1955.)

The previously described method of wave diagrams for the study of one-dimensional, nonsteady gas flow (*CAL-14-M*) is extended to include the propagation of plane flame fronts in ducts. From the wave diagram, all state and flow parameters may be obtained at any time and at any point along the duct. The flame is treated as an entropy discontinuity and it is assumed that the pressures on both sides of the flame front are equal. The error of the latter assumption is shown to reach 10% for effective burning velocities of 10% of the speed of sound in the unburned gas. The effective burning velocity is assumed to be independent of pressure and proportional to the absolute temperature of the unburned gas.

16 Addition of Heat to a Gas Flowing in a Pipe at Subsonic Speeds, by J. V. Foa and G. Rudinger, Cornell Aeronautical Laboratory, *J. Aero. Sci.*, vol. 16, no. 2, pp. 84–95, Feb. 1949, *CAL-48-P.*

It is shown that, contrary to widely accepted opinions: (a) The addition of heat to a subsonic flow in a pipe modifies the flow conditions both downstream and upstream of the region of heat addition. (b) The Mach number of the heated flow does not necessarily increase, approaching the sonic state, when heat is added; instead, it will increase or decrease depending on the boundary conditions. (c) The static temperature of the gas does not decrease when heat is added within the range of initial Mach numbers from $1/\sqrt{\gamma}$ to 1.0; instead, it increases continuously. (d) The attainment of sonic velocity in the heated region does not limit the amount of heat that can be added. (e) The mass flow may decrease as a result of the addition of heat but this decrease is in no way related to the attainment of sonic velocity in the heated region. A quantitative treatment of the problem is presented for the cases of greatest practical interest, and numerical examples are given to illustrate the procedures and conclusions.

17 An Evaluation of the Heat Transfer Encountered in a Rocket Motor Operating at High Chamber Pressures, by C. F. Warner and M. J. Zucrow, Purdue University, July 1949, *PUR-21-R.*

The theoretical rates of heat transfer between the walls of a 500-lb-thrust rocket motor and the combustion gases resulting from the oxidation of octane and aniline by white fuming nitric acid are obtained as a function of the rocket motor chamber pressure. The convective heat transfer coefficients, obtained by using the McAdams correlation, are compared with the rates obtained by the Humble-Lowdermilk-Grele correlation. The radiant heat transfer rates are obtained by the Hottel-Egbert method. It was found that the chamber and nozzle heat transfer rates increase linearly with chamber pressure and that the nozzle heat transfer rates become extremely high at chamber pressures beyond 1500 psia.

18 Regularity of Turbulent Flow in Smooth Pipes, by I. Nikuradse, translated by F. W. Bowditch, W. G. Agnew, and H. J. Buttner, Purdue University, Aug. 1949, *PUR-11-M.*

A thorough experimental and analytical treatment of turbulence in smooth pipes.

19 Linearized Solution of Nonsteady Flows Through Ducts, by W. Squire and T. R. Goodman, Cornell Aeronautical Laboratory, March 1950, *CAL-33-M.*

This paper seeks a linear solution periodic in time for air flowing in a tube of finite length which is moving at a constant velocity in the direction of its axis. The linearization is performed in such a way that the differential equations and boundary conditions for the higher order solutions are readily derived; the general solution is carried out only for first-order terms.

20 Forced Shock Oscillations in Diffusers, by J. G. Logan, Jr., Cornell Aeronautical Laboratory, April 1950, *CAL-12-M.*

An experimental technique for the study of shock motion in diffusers under the influence of downstream pressure oscillations is described. The results of preliminary experiments indicate that the maximum pressure amplitude of these disturbances that will permit the shock to be retained in a diffuser is approximately a linear function of diffuser length and frequency. These experimental results are compared with those predicted theoretically by Kantrowitz.

21 Progress Report on the Stability of Liquid Films for Cooling Rocket Motors, by M. J. Zucrow, C. M. Beighley, and E. Knuth, Purdue University, Oct. 1950, *PUR-22-R.*

A preliminary report is made of an experimental study of cooling rocket motor walls by injecting liquids through slots to form a liquid film along the wall while air is blown through the test station. Visual determination of the point at which the liquid separates and flows into the air stream rather than along the wall shows that as the velocity of the air increases, the velocity of liquid flow can be increased. The width of the injection slot, the angle of injection, and the viscosity and density of the liquid influence the maximum rate for nonseparating flow; the attitude of the injector, the surface tension of the liquid, and the size of the gas duct do not affect it.

22 Laurent Schwartz's Theory of "Distributions" and Some of Its Applications (Fourier Transformation), by G. B. Melese, Johns Hopkins University, Sept. 1951, *JHU-2-R.*

This paper abstracts essentially the practical results of Laurent Schwartz's theory of "distributions" from his two books published in French. It is written for applied mathematicians and theoretical physical scientists. The notion of "function" is first generalized to "measure" (Dirac delta function) and then to "distribution" (derivatives of delta function). With the new notion of distributions, justifications are given for many (previously heuristic) manipulations of discontinuities encountered in the solutions of partial differential equations.

23 Nonsteady Flow in Straight Ducts, by Carlo Ferrari, translated by R. H. Cramer, Cornell Aeronautical Laboratory, Nov. 1951, *CAL-43-M.*

The nonsteady flow of a liquid or gas in a straight duct, whose sides may be deformed by the pressure fluctuations occurring therein, is studied by means of the method of characteristics. Although the behavior of the flow is nonlinear, a closed-form (parametric) solution is derived, and a practical application of the result is made to the analysis of the fuel inlet system of a diesel engine. The trick which enables the derivation of the simple solution is the replacement of the actual equation of state by a fictitious one; but, by use of a similarity rule, the transfer between the real system and the more mathematically wieldy fictitious one is easily accomplished. A generalization of the problem is stated for the case in which the changes of state are not isentropic; for example, when chemical reactions occur within the fluid.

24 Turbulence of Supersonic Flow, by L. S. G. Kovasznay, *J. Aero. Sci.*, vol. 20, no. 10, pp. 657–675, Oct. 1953, *JHU-4-P.*

First-order perturbation theory indicates that the Navier-Stokes equations for a compressible, viscous, and heat-conductive gas can have three distinctly different types of disturbance fields, obeying three independent differential equations. These three "modes" of disturbance fields are: vorticity mode, entropy mode, and sound wave mode The modes are independent when the intensities of the fluctuations are small, but they interact at larger intensities when linearization is not permissible.

The principal tool for measuring the fluctuating fields is the hot-wire anemometer adapted for supersonic flow. In a supersonic flow the hot-wire anemometer responds to two variables: mass flow fluctuations and stagnation temperature fluctuations. Each of the above three modes contributes to both of these variables. By taking measurements at different wire temperatures, the relative sensitivity to the flow parameters varies and a "fluctuation diagram" can be obtained The character of the fluctuation diagram differs for each mode, and even coexisting modes can be separately determined by analyzing the fluctuation diagram under certain restrictive conditions.

Hot-wire measurements were obtained in various supersonic flows. Pure temperature spottiness (entropy mode) and pure sound wave fields were explored. Detailed measurements were taken in a turbulent supersonic boundary layer. With the aid of the fluctuation diagram, the intensity of tem-

perature spottiness (entropy mode) and of turbulent velocity fluctuations (vorticity mode) was measured across the layer. Energy spectrum and probability density measurements gave clues concerning the character of the fluctuations.

25 Eddy Turbulence and Random Sound in a Compressible Fluid, by M. S. Uberoi, Johns Hopkins University, *Proc., Cambridge Philos. Soc.*, vol. 49, part 4, pp. 732–734, Oct. 1933, *JHU-5-P.*

An analysis is presented which shows that for a given velocity correlation based on a statistical average, any turbulence field can be decomposed into two uncorrelated parts. One part corresponds to eddy turbulence and the other to random sound.

26 A Theoretical and Experimental Study of Finite Amplitude Wave Interactions With Channels of Varying Area, by A. Kahane, W. R. Warren, W. C. Griffith, and A. A. Marino, *J. Aero. Sci.*, vol. 21, Aug. 1954, *PR-53-P.*

A theoretical and experimental investigation has been made of the interaction of waves of finite amplitude in ducts of varying cross section. A new one-dimensional method is described by which the steady-state conditions after passage of an isentropic wave may be obtained from a chart without necessity of previously required iterative procedures. The chart has proved useful in the discussion of the spectrum of physical solutions which has been presented herein.

Experiments were carried out in a shock tube to indicate the nature of the actual two-dimensional interaction processes occurring, and to determine how accurately one-dimensional methods could be applied to such interactions. A two-dimensional channel of area ratio 0.504 was made in such a way that the normal shock wave could be incident on either end. Density fields were measured with the aid of a Mach-Zehnder interferometer.

Comparison of the transient density distribution obtained in the center of the channel with results of a one-dimensional unsteady flow calculation for the converging channel indicates excellent agreement. The establishment of steady flow was observed for a wide variety of incident shock strengths using both the converging and the diverging models. The isentropic theory fits the measured densities well for weak shocks. Satisfactory agreement is obtained for strong shocks using real shock theory.

27 Analysis of Turbulent Density Fluctuations by the Shadow Method, by M. S. Uberoi and L. S. G. Kovasznay, Johns Hopkins University, *J. Appl. Phys.*, vol. 26, no. 1, pp. 19–24, Jan. 1955, *JHU-7-P.*

Shadow pictures of turbulent flow regions give a particular kind of information about the three-dimensional density field. If homogeneity and isotropy of the fluctuation field can be assumed, the statistical properties of the picture uniquely determine the correlation function or power spectrum of the three-dimensional turbulent density field. Shadow pictures obtained in the wake of a supersonic projectile were analyzed in this manner and encouraging results were obtained. In order to check the validity of the method, the density fluctuations in a heated jet were measured both by the shadow method and by the more conventional hot-wire technique.

28 On Axisymmetric Turbulence, by G. B. Melese, Johns Hopkins University, June 1954, *JHU-6-R.*

The kinetic problem of axisymmetric turbulence is considered. Properties of directly measurable two-point correlations caused by incompressibility, homogeneity, and axisymmetry are derived for first-, second-, and third-order correlation tensors. Equations are derived for correlation functions which express the pressure-velocity correlation as a function of triple correlations in the dynamics of axisymmetric turbulence. A solution is given for double velocity correlations in the asymptotic state for small Reynolds numbers. Fourier transforms of the correlations are introduced, and the energy and the one-dimensional spectrums are defined. Results are obtained for small and large wave numbers, and the spectrum is obtained in the case of small Reynolds numbers.

29 On the Reflection of Shock Waves From an Open End of a Duct, by G. Rudinger, Cornell Aeronautical Laboratory, Aug. 1954, *CAL-61-P.* Presented at the Second Canadian Symposium on Aerodynamics, Toronto, Feb. 25–26, 1954. Also submitted to *J. Appl. Phys.*

The readjustment of the mean exit pressure to its steady-flow equilibrium level, following the arrival of a shock wave at an open end of a duct, has been investigated. The same problem was also attacked experimentally using a shock tube 3.23 in. ID. It was found that the exit pressure deviates appreciably from its steady-flow equilibrium value during a time in which a sound wave could travel about three duct diameters. Satisfactory agreement between theory and experiment was observed for shock pressure ratios up to about 1.9 (in air) although, near this limit, significant deviations due to wall friction were observed toward the end of the pressure decay region. For still stronger shocks, the influence of the decay time on the phenomena inside the duct becomes unimportant while friction effects dominate.

30 The Static Pressure Variation in Compressible Free Jets, by W. R. Warren, Jr., Princeton University, *J. Aero. Sci.*, vol. 22, March 1955, *PR-64-P.*

Mean static pressure profiles taken during investigations of the mixing of compressible jets with quiescent air were found to give insight into the physical structure of a spreading jet. The widely accepted assumption that the static pressure of a jet does not vary is not always exactly true. Results were obtained for initial Mach numbers of 0.97 and 2.60.

31 Improved Wave Diagram Procedure for Shock Reflection From an Open End of a Duct, by G. Rudinger, Cornell Aeronautical Laboratory, *J. Appl. Phys.*, vol. 26, no. 11, pp. 1339–1341, Nov. 1955, *CAL-65-P.*

The recently derived improved boundary conditions for the reflection of weak shock waves from an open end of a duct can be well approximated by a centered expansion wave if the center of the latter is located on the leading characteristic of the reflected wave and at some distance e outside the duct. An empirical formula

$$e/D = \left(0.90 + \frac{0.677}{(p_1/p_0) - 1}\right)(\gamma + 1.08) - 3.8$$

was derived, where D is the duct diameter, p_1/p_0 the shock pressure ratio, and γ the specific heat ratio. This result allows application of the improved boundary conditions without losing the convenience of the customarily used wave diagram procedure.

32 Interaction of a Shock-Wave and Turbulence, by L. S. G. Kovasznay, Johns Hopkins University, presented at the Heat Transfer and Fluid Mechanics Institute meeting, June 1955, *JHU-8-P.*

An attempt was made to demonstrate experimentally the interaction between the random fluctuation field and a strong shock wave. An axisymmetric wake is passed through an oblique shock produced by a wedge. Hot-wire anemometer surveys of the turbulent fluctuations were made to explore the different modes. A comparison was made of the fluctuations in the wake before and after the passage through the shock, and sound waves emanating from the interaction zone were located.

33 On the Classification of Normal Detonation Waves, by T. C. Adamson, Jr., and R. B. Morrison, University of Michigan, JET PROPULSION, vol. 25, p. 400, Aug. 1955, *MICH-1-M.*

A classification of normal detonation waves is proposed which involves the definition of a heat release function F that depends upon the incoming velocity and temperature and the heat released by the unburned mixture per unit mass. A Chapman-Jouguet detonation wave corresponds to $F = 1$; $1 < F < 2$ corresponds to a strong detonation wave; and $F = 2$ corresponds to a shock wave.

34 A Flow Instability Following Shock Reflection from a Flared End of a Duct, by G. Rudinger and L. M. Somers, Cornell Aeronautical Laboratory, JET PROPULSION, Oct. 1955, *CAL-67-M.*

Studies indicated that violent pressure oscillations may occur in a duct following the reflection of a shock wave from a flared end. These oscillations could be qualitatively explained by alternate periods of separation and reattachment of the flow in the flare. This view is supported by high-speed schlieren motion pictures of the flow just outside the exit of the flare. The pictures show that a number of vortices are emitted from the duct when pressure oscillations appear. The instability occurs only when the flow becomes supersonic in part of the flare.

35 On an Initial Value Problem of an Unbounded Incompressible Viscous Flow, by Tse-Sun Chow, Johns Hopkins University, submitted to *J. Rational Mech. Analysis*, Nov. 1955, *JHU-9-T-P.*

An attempt was made to analyze the interaction of the various Fourier components with each other which occur as a result of the nonlinearity of the Navier-Stokes equation when applied to the problem of unbounded incompressible viscous flow. An investigation is made of the subsequent development of the motion of an unbounded viscous incompressible fluid when initially its motion is described by two spatially periodic waves. The solution to this problem is carried out by successive approximation, and the existence of the solution is proved. The velocity and pressure fields are first expressed in a Fourier representation, and the Navier-Stokes and continuity equations are then transformed into equations for the Fourier components.

36 Maximum Production of Vorticity in Isotropic Turbulence, by R. Betchov, Johns Hopkins University, submitted to *J. Fluid Mech.*, March 1956, *JHU-10-P.*

Given the following quantities: x_i, the Cartesian coordinates; $\mathbf{u}_i$, the velocity vector $\mathbf{u}_{i_j} = \mathbf{u}_i/x_j$; $\mathbf{u}_{i_j} = s_{i_j} + r_{i_j}$, where s_{i_j} is the symmetric rate of strain tensor; and a, b, and c the eigenvalues of s_{i_j}. With $< >$ indicating the averaged (time or ensemble average) quantity, the following modified inequality is proved

$$\pm <abc> \leqq \frac{1}{3\sqrt{3}} [<(a^2 + b^2 + c^2)>1/2 \quad <(a^4 + b^4 + c^4)>1/2]$$

Relations, conditions, and conclusions are developed for these parameters.

37 The Influence of Finite Observation Interval on the Measurement of Turbulent Diffusion Parameters, by Y. Ogura, Johns Hopkins University, March 1956, *JHU-11-P.*

An analysis is made of the errors involved in confining measurements of turbulent diffusion in the atmosphere to finite observational intervals. Formulas are derived that show the influence of a finite observation interval on the correlation functions and the influence of an observation interval on the measured spectrum. The results show that the

turbulent level is important in determining the relationship between the Eulerian and Lagrangian time intervals of observation.

38 On the Interaction of a Chapman-Jouguet Detonation Wave With a Wedge, by Rudi S. B. Ong, University of Michigan, March 1956, *MICH-3-T.*

The regular reflection of a C-J detonation is examined experimentally and theoretically. It turns out to be similar to the case of an incident shock wave. It is possible to determine and construct an approximate configuration for the reflected shock wave in the problem of Mach reflection with satisfactory accuracy for wedge angles up to 15 deg. The analysis is not limited to weak waves.

39 On the Interaction of Weak Disturbances and a Plane Shock of Arbitrary Strength in a Perfect Gas, by C. T. Chang, Johns Hopkins University, submitted to *J. Aero. Sci.*, May 1956, *JHU-12-P.*

The effect on the flow field downstream of a plane shock due to a weak step-function entropy disturbance upstream is studied. A governing equation for the perturbed pressure is derived which is hyperbolic or elliptic according to the range of its variables. In the hyperbolic region the method of characteristics is used. In the elliptic region a transformation to a Laplace equation is made. Then, using the method of conformal mapping, the problem is reformulated in a complex half plane.

40 On the Interaction of a Weak Upstream Disturbance With an Infinitely-Extended Plane Shock of Arbitrary Strength, by C. T. Chang, Johns Hopkins University, submitted to *Quart. Appl. Math.*, May 1956, *JHU-13-P.*

The problem of the interaction between an upstream disturbance and a plane shock of infinite extent is investigated. For a normal shock, there is a critical angle of the upstream disturbance relative to the shock such that (a) for angles greater than the critical, the sound wave generated downstream attenuates; (b) for angles less than the critical, the sound wave generated downstream does not attenuate. For an oblique shock, two critical angles exist. When the downstream sound waves are not attenuated, there is no phase shift in the disturbance across the shock; but, when the downstream sound waves are attenuated, a phase shift does occur.

41 Measurements on Gaseous Detonation Waves, by J. A. Nicholls, R. B. Morrison, and R. E. Cullen, University of Michigan, presented at the Second Symposium on Detonation, Office of Naval Research, Feb. 1955, *MICH-2-P.*

An analysis of one-dimensional, steady detonation waves is presented which emphasizes the dynamic properties of velocity and heat release. The analysis shows that two types of detonation are possible: the Chapman-Jouguet type and the strong detonation. A comparison of heat release as a function of detonation Mach number is made between the simplified theory presented and the results of shock tube experiments. The experimental data correlate reasonably well with the theory, although the slope of the experimental curve differs from that of the theory.

A number of spark schlieren photographs are presented which indicate the initiation of the steady detonation, the interaction of the wave with a wedge, and the possibility of a spinning detonation.

III Chemical Processes

A Reaction Kinetics

1 The Ignition of n-Butane by the Spontaneous Oxidation of Zinc Dimethyl, by E. J. Badin, D. R. Walter, and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 69, pp. 2586–2588, Nov. 1947, *PR-31-P.*

The oxidation of zinc dimethyl with oxygen in clean pyrex bulbs has been studied. The effect of nitrogen, helium, and n-butane as inerts on the slow oxidation has been determined. It has been shown that the ignition of a hydrocarbon, n-butane, may be initiated by the explosive zinc dimethyl oxidation at room temperature.

2 Oxidation of Metal Alkyls and Related Compounds; The Ignition of Hydrocarbons, by E. J. Badin, Princeton University, Third Symposium on Combustion, Flame, and Explosion Phenomena, Williams and Wilkins, Baltimore, pp. 386–389, Sept. 1948, *PR-23-P.*

This paper contains a brief summary of the oxidation behavior of metal alkyls, metal carbonyls, and metal boron-hydrides. Some exploratory work on their ability to act in initiating hydrocarbon combustion with its possible implications on the knock problem is discussed.

3 The Atomic Hydrogen-Molecular Oxygen Reaction and Hydrocarbon Oxidation Initiated by Atomic Hydrogen at Low Pressures, by E. J. Badin, Princeton University, Third Symposium on Combustion, Flame, and Explosion Phenomena, Williams and Wilkins, Baltimore, pp. 382–385, Sept. 1948, *PR-24-P.*

This paper represents a summary of some recent experimental work on the reaction between atomic hydrogen produced by electrical discharge and molecular oxygen. The reaction study has been extended to a higher temperature range than heretofore and surface effects on the reaction determined. Some results on the oxidation of C_4 hydrocarbons initiated by atomic hydrogen are also presented.

4 The Reaction Between Atomic Hydrogen and Molecular Oxygen at Low Pressures, by E. J. Badin, Princeton University, *J. Amer. Chem. Soc.*, vol. 70, pp. 3651–3655, Nov. 1948, *PR-5-M-P.*

In the low temperature reaction (−196 C), peroxide and water formed are proportional to the oxygen at low concentrations. The effect on the reaction of pyrex, potassium chloride, and phosphoric acid surfaces at higher temperatures has been determined. The results observed have been ascribed primarily to the "wetness" of the surface. Recombination of OH (as well as H) on the surface lead to decreased peroxide and water formation.

5 Hydrocarbon Oxidation Initiated by Atomic Hydrogen, by E. J. Badin, Princeton University, *J. Amer. Chem. Soc.*, vol. 70, no. 11, pp. 3965–3966, Nov. 1948, *PR-13-M-P.*

Summarizes work on the initiation of hydrocarbon oxidation (methane, propane, propylene, n-butane, isobutane, 1-butene and 2-butene) by atomic hydrogen using the discharge tube method. Definite information regarding the course of the oxidation in regard to primary oxidation products and relative rates of oxidation is presented. Particular attention has been paid to isobutane. A discussion of the results obtained is given.

6 Wall Effects in the Oxidation of Boron Triethyl Vapor. The Ignition of n-Butane, by R. S. Brokaw, E. J. Badin, and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 70, no. 5, pp. 1921–1922, May 1948, *PR-30-P.*

Boron triethyl vapor ignites spontaneously in oxygen at partial pressures below 1 mm in a pyrex bulb held at 0 C. The product of minimum pressure and bulb diameter is constant, indicating that chains start in the gas phase and end on the wall. When the glass surface is coated with reaction products, the minimum pressure is greater. There is evidence of a cool flame phenomenon. Boron triethyl will ignite an n-butane-oxygen mixture within narrow pressure limits.

7 Spontaneous Ignition of Nickel Carbonyl Vapor. The Ignition of n-Butane, by E. J. Badin, P. C. Hunter, and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 70, no. 6, pp. 2055–2056, June 1948, *PR-29-P.*

Nickel carbonyl vapor explodes in air or oxygen at 20 C and partial pressures as low as 15 mm. Explosion is preceded by a long and variable induction period. The existence of an explosion limit and induction period suggests a chain process. The exact mechanism of initiation is not known. Addition of nickel carbonyl to an n-butane-oxygen mixture causes the latter to react at 20–40 C.

8 A Further Study of the Kinetics of Thermal Decomposition of Aluminum Borohydride, by R. S. Brokaw, Princeton University, March 1949, *PR-12-M.*

The decomposition of aluminum borohydride has been studied at 159 and 189 C, and the disappearance of aluminum borohydride with time has been followed. The effect of various surfaces on the decomposition rate has been shown to be slight at 159 C. A possible mechanism for the decomposition is proposed.

9 Preliminary Study of the Kinetics of Pyrolysis of Diborane, R. P. Clarke and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 73, no. 5, pp. 2132–2134, June 1949, *PR-14-M-P.*

The kinetics of pyrolysis of diborane have been studied between 85 and 163 C. The fractional rate appears to be proportional to the square root of the initial pressure times the $^5/_2$-power of the fraction of diborane unreacted, and is depressed by addition of hydrogen but unaffected by an equivalent amount of nitrogen or by an increase in surface. The reaction is believed to be a radical-type polymerization process complicated by quasi-reversible dehydrogenation.

10 The Thermal Oxidation of Hydrazine Monohydrate in the Vapor Phase, by J. M. Nelson and D. E. Holcomb, Purdue University, June 1949, *PUR-7-M.*

Vapor pressure of hydrazine monohydrate was determined over the temperature range 27.6 to 120 C. Vapor pressure is lower than of pure hydrazine or H_2O at the same temperature. Equation given for determination of vapor pressure which is accurate within ±2 per cent. Experimental data indicate complete dissociation into hydrazine and water in temperature range 71.2–151.2 C. Thermal oxidation by oxygen was studied in constant volume reactor of pyrex. Experiments were carried out under isothermal conditions and with various concentrations of hydrazine, oxygen, water, and nitrogen. A series of runs was made with each component present in large excess.

11 Spontaneous Ignition of Aluminum Borohydride Vapor in Oxygen, by E. J. Badin, P. C. Hunter, and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 71, no. 8, p. 2950, Aug. 1949, *PR-27-P.*

Mixtures of aluminum borohydride and oxygen at room temperature either exploded or did not react at all over a 17-minute period. With dry oxygen, no explosion occurred upon filling vessel over pressure range from 1 to 300 mm. Upon subsequent evacuation, ignition almost always occurred. With moist oxygen there was always explosion.

12 Kinetics of the Non-Catalytic Oxidation of Ammonia: Flow Experiments, by E. R. Stephens and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 72, no. 3, pp. 1188–1190, March 1950, *PR-10-M-P.*

The slow noncatalytic reaction between ammonia and oxygen has been studied by the flow method. It has been found that the fraction reacted increases rapidly as the ammonia concentration is decreased, indicating a zero (or negative) order. Thus ammonia

appears to inhibit its own oxidation. Rates in empty and packed reaction tubes are about the same; but coating with potassium chloride causes a marked decrease in both cases.

13 The Low Temperature, Low Pressure, Hydrogen Atom Initiated Combustion of Hydrocarbons, by E. J. Badin, Princeton University, *J. Amer. Chem. Soc.*, vol. 72, no. 4, pp. 1550–1553, April 1950, *PR-28-P.*

During combustion of isobutane at low pressure, peroxide is formed at the wall and contains the hydroperoxide group as indicated by infrared spectra. Conditioning of the wall is important. Rates and products of oxidation of CH_4, C_2H_6, n-C_4H_{10}, i-C_4H_{10}, 1-C_4H_8, 2-C_4H_8 are studied.

14 The Oxidation of Butene-1 Induced by Aluminum Borohydride, by R. S. Brokaw, E. J. Bodin, and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 72, no. 4, pp. 1793–1795, April 1950, *PR-34-P.*

For the induced combustion of C_4 hydrocarbons with aluminum borohydride, n-butane gave no explosion, butene-1 exploded after an induction period, and butadiene-1,3–induced combustion of butene-1 has been carried out. The limits and effect of total pressure for the reaction have been determined. For the latter case, an upper and lower limit characteristic of chain activation and deactivation has been observed.

15 Kinetics of the Thermal Decomposition of Diborane, With a Review of Structure Data, by R. P. Clarke and R. N. Pease, Princeton University, July 1950, *PR-16-M.*

A study has been made of the rate of decomposition of diborane in a static system from 85 to 163 C employing starting pressures up to 160 mm Hg. The over-all effect is that of chain reaction polymerization of B_2H_6 to $(BH)_x$. Evidence is given for an initial $^3/_2$-order step. A mechanism is proposed which included back-reactions involving the respective partial pressures of hydrogen, diborane, and the volatile intermediates.

16 The Kinetics of the Reaction of Aluminum Borohydride Vapor With Olefins, by R. S. Brokaw and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 72, no. 7, pp. 3237–3241, July 1950, *PR-9-M-P.*

The reactions between aluminum borohydride vapor, $(Al(BH_4)_3)$, and ethylene, C_2H_4, propylene, C_3H_6, and butene-1, C_4H_8, have been studied; and the kinetics have been found to be first order with respect to the aluminum borohydride pressure and independent of the olefin concentration. The activation energy has been determined, and a reaction mechanism is proposed. All three reactions occur at nearly the same rate. Boron alkyls are products of the reactions. The reactions are of interest in their bearing in the oxidation of the hydrocarbons induced by borohydride vapor.

17 The Effect of Traces of Oxygen on the Reaction of Aluminum Borohydride With Ethylene, by R. S. Brokaw and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 72, no. 11, pp. 5263–5266, Nov. 1950, *PR-15-M-P.*

The effect of traces of oxygen on the reaction between aluminum borohydride and ethylene has been studied. It is found that the reaction is accelerated by oxygen and inhibited by a reaction product and by increased surface area. An equation which qualitatively describes the experimental results is given, and a possible mechanism is proposed. A few experiments on the induced combustion and ethylene with aluminum borohydride and with borotriethyl have been performed.

18 Hypergolic Reaction of Dicyclopentadiene With White Fuming Nitric Acid, by C. H. Trent and M. J. Zucrow, Purdue University, *J. Amer. Rocket Soc.*, vol. 21, no. 5, May 1951, *PUR-13-P.*

The photographic study of the hypergolic reaction between dicyclopentadiene and anhydrous nitric acid indicates that a solid phase is formed prior to ignition and that the ignition of the propellant is propagated from the solid phase. The latter has been isolated. Although the identity of the solid phase remains unknown, characterization tests have indicated that it is a nitrated polymer containing the nitro group and the nitrate ester group.

19 Kinetics of the Non-Catalytic Oxidation of Ammonia: Static Experiments in an Empty Uncoated Silica Vessel, by E. R. Stephens and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 74, no. 14, pp. 3480–3482, Feb. 1952, *PR-36-P.*

A study of the oxidation of ammonia in an uncoated silica reaction vessel indicates that the rate increases in passing from ammonia rich to ammonia lean mixtures. On the rich side, rates are roughly proportional to the product of ammonia and oxygen concentrations, whereas on the lean side the square of the oxygen concentration seems to be involved. The activation energy approximates 45,000 cal in both regions.

20 Azomethane-Induced Oxidation of Propane, by M. Scheer and H. Taylor, New York University, *J. Chem. Phys.*, vol. 20, no. 4, pp. 653–657, April 1952, *NYU-25-P.*

The effect of methyl radicals from the photolysis of azomethane on propane-oxygen mixtures in pyrex vessels has been shown to include a slow oxidation in the temperature range 35 to 200 C and cool flames at 250 C. Azomethane decomposed thermally induces cool flames in propane-oxygen mixtures at 255 and 270 C, temperatures below those at which cool flames occur in the system propane-oxygen alone. A rapid photo-oxidation has been observed in a quartz vessel in the temperature range 200 to 250 C.

21 Kinetics of the Thermal Decomposition of Aluminum Borohydride, by R. N. Pease and R. S. Brokaw, Princeton University, *J. Amer. Chem. Soc.*, vol. 74, no. 6, pp 1590–1591, June 1952, *PR-18-P.*

The rate of thermal decomposition of gaseous aluminum borohydride at 159 and 189 C is reported. It is concluded that the reaction is first order and homogeneous. The mechanism has not yet been determined.

22 Behavior of Liquid Hydrocarbons with White Fuming Nitric Acid, by M. J. Zucrow and C. H. Trent, Purdue University, *Ind. Eng. Chem.*, vol. 44, no. 11, pp. 2668–2673, Nov. 1952, *PUR-18-P.*

Each of 20 liquid hydrocarbons was mixed rapidly with anhydrous HNO_3, and temperature-time curves were obtained with a specially designed apparatus. Maximum temperature and time to reach maximum temperature are reported. Ignition temperatures were also measured by means of a separate apparatus for several hydrocarbons and mixtures of hydrocarbons with HNO_3 as oxidizer. Other studies were made with HNO_3 containing H_2O or NO_2. The work indicates that unsaturated hydrocarbons, particularly diolefins, promote rapid reaction with HNO_3 and have relatively low ignition temperatures. Aromatic hydrocarbons, however, despite their rapid reaction rate, have high ignition temperatures.

23 The Thermal Oxidation of Hydrazine Vapor, by W. I. H. Winning, Princeton University, *J. Chem. Soc.*, pp. 926–931, March 1954, *PR-49-P.*

The thermal gas phase reaction between hydrazine and oxygen shows none of the chain characteristics of, e.g., the hydrocarbon series. It is predominantly surface reaction, the activation energy of which, below 100 C, was found to be 6430 cal/mole. On comparison with the absolute reaction rate expression for a bimolecular surface reaction, unrelated by the products, and in which neither reactant is strongly adsorbed, very good agreement is obtained between the experimental and the theoretical rate value.

24 A Kinetic Study of the Diborane-Ethylene Reaction, by A. T. Whatley and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 76, no. 3, pp. 835–838, March, 1954, *PR-50-P.*

The combination of ethylene with diborane yielding boron triethyl as a final product proceeds in the range 120–175 at a rate given by $-dp/dt = k(B_2H_6)^{3/2}(1 - a(B_2H_6)/(C_2H_4))$. As the equation indicates, the reaction becomes mildly explosive when B_2H_6/C_2H_4 ratio is sufficiently increased (beyond about 0.5); and the excess of diborane is consumed in the process. A mechanism of ethylene addition is proposed.

25 Observations on Thermal Explosions of Diborane-Oxygen Mixtures, by A. T. Whatley and R. N. Pease, Princeton University, *J. Amer. Chem. Soc.*, vol. 76, no. 7, pp. 1997–1999, July 1954. *PR-51-P.*

Diborane-oxygen mixtures explode after an induction period within a range of concentrations at 105 C to 165 C. Since slow decomposition of diborane is occurring simultaneously at these temperatures, a pyrolysis product—perhaps pentaborane—may be the normal sensitizing agent. Both hydrogen and ethylene narrow the explosion limits.

26 The Surface Migration of Carbon on Tungsten, by R. Klein, Bureau of Mines, *J. Chem. Phys.*, vol. 22, no. 8, pp. 1406–1413, Aug. 1954, *BUM-11-P.*

The surface migration of carbon on tungsten was observed with the field emission microscope technique. The tungsten point was shadowed with carbon and heated to a given temperature; observations of the emission patterns were made at room temperature at various time intervals. The migration occurs at a measurable rate starting about 850 K. It is characterized by a sharp boundary of a form which clearly shows that the (011)- and (121)-planes are avoided. An activation energy of 55 ± 7 kcal/mole was calculated for the process by application of the theory of diffusion with a sharp moving boundary.

27 A New Shock Tube Technique for the Study of High Temperature Gas Phase Reactions, by H. S. Glick, W. Squire, and A. Hertzberg, Cornell Aeronautical Laboratory, Fifth Combustion Symposium Volume, 1955, April 1955, *CAL-63-P.*

A modified shock tube was developed in which a sample of gas could be heated by a single high temperature pulse of known shape and duration. Preliminary studies were conducted on the reaction $^1/_2N_2 + {}^1/_2O_2 \rightleftarrows$ NO. From 2500 to 3000 K, concentrations of NO were found which closely approached the equilibrium values. An estimate of the reaction rate was made by assuming a bimolecular mechanism from the data obtained below 2500 K. A least-square fit of the specific reaction rate constant data gave an activation energy of 40 kcal/mol.

28 Reaction of Paraffin Hydrocarbons with Ionized Oxygen. Possible Role of Ozone in Normal Combustion, by C. C. Schubert, and R. N. Pease, Princeton University, submitted to *J. Amer. Chem. Soc.*, Nov. 1955, *PR-58-M.*

A study was undertaken of the thermal reaction between ozonized O and the lower paraffin hydrocarbons. Literature was reviewed concerning the possible role of O_3 as an intermediate in hydrocarbon-O reaction scheme; this reaction might be related to the phenomenon of the detection of O_3 in smog.

29 The Vapor Phase Infra-Red Spectra of the Ozonides of Ethylene, Propylene and Isobutylene, by C. C. Schubert and D. Garvin, Princeton University, submitted to *J. Amer. Chem. Soc.*, Nov. 1955, *PR-61-M.*

The ozonides of ethylene, propylene, and

isobutylene after ozonization at −78 C in an inert solvent showed no strong absorption in the carbonyl region (about 5.7 2). Vapor phase infrared spectra are presented which indicate that any absorption in the 5.7 μ region is weak compared with absorptions at other wavelengths. Pure isobutylene ozonide was very resistant to decomposition in the presence of water vapor, but showed rapid hydrolysis in concentrated HCl. The results suggest that ozonide identification should be based on characteristic bands in spectral regions other than the carbonyl region.

30 The Oxidation of Lower Paraffin Hydrocarbons. Part I. Room Temperature Reaction of Methane, Propane, n-Butane and Isobutane with Ozonized Oxygen, by C. C. Schubert and R. N. Pease, Princeton University, submitted to *J. Amer. Chem. Soc.*, Jan. 1956, *PR-62-P*.

Results are given for the reaction between ozonized O (about 3 mol per cent O_3) and the paraffins CH_4, C_3H_8, C_4H_{10}, and isobutane within the 25 to 50 C range. The reaction rates were measured *in situ* on the infrared absorption of the reacting gases. The pre-exponential terms, estimated on the basis of a reaction rate $\alpha[O_3]\cdot[HCl]$, were 7.2×10^{10} cc/mole/sec for the CH_4-O_3 reaction, 3.1×10^9 for C_3H_8-O_3, 8.2×10^8 for C_4H_{10}-O_3, and 4.4×10^8 for isobutane.

31 A Comparison of Three Methods for the Analysis of Gaseous Ozone, by C. C. Schubert and D. Garvin, Princeton University, submitted to *J. Anal. Chem.*, March 1956, *PR-63-P*.

O_3 at low concentrations in air or O was analyzed by three methods: absorption in aqueous KI followed by titration with $Na_2S_2O_3$; IR absorption; and measurement of the gas volume increment upon thermal decomposition. The titration method as applied in a flow system is not precise for gas streams containing more than 1 mol per cent of O_3. At higher concentrations, errors occur which tend to reduce the observed O_3 concentration below that actually present. The recommended method for the analysis of gases containing 2 to 100 mm Hg of O_3 is infrared absorption based on a calibration curve obtained from absolute method analyses.

32 The Oxidation of Lower Paraffin Hydrocarbons. Part II. Observations on the Role of Ozone in the Slow Combustion of Isobutane, by C. C. Schubert and R. N. Pease; submitted to *J. Amer. Chem. Soc.*, April 1956, *PR-65-P*.

The reaction of ozonized O (3 to 6 mole per cent O_3) with isobutane from 110 to 270 C was compared with the slow uncatalyzed reaction with O alone. The O_3-induced oxidation merged in the slow combustion reaction at about 265 C. Results suggested that O_3 may be the active intermediate which is responsible for chain branching during the slow combustion of hydrocarbons in O. O_3 might result from the reaction: $RO_2\cdot + O_2 \rightarrow O_3 + RO\cdot$; O_3 probably has the stability requirements to account for the cool flame reaction and negative temperature coefficient region which are observed in the combustion of hydrocarbons.

B Thermodynamics and Thermochemistry

1 The Formation of Nitric Oxide in Flames: Calculations for Methane-Oxygen-Nitrogen Mixtures, by R. S. Brokaw, Princeton University, July 1948, *PR-7-M*.

Calculations have been made to ascertain the equilibrium concentrations of nitric oxide in methane-oxygen-nitrogen flames. Under optimum conditions about 2.2 per cent nitric oxide may be formed. The calculations are in qualitative agreement with experimental data in the literature.

2 Heat of Combustion of Nitrogen Containing Compounds, by M. V. Sullivan, G. M. Kibler, and H. Hunt, Purdue University, July 1948, *PUR-3-M*.

The heats of combustion were determined for several compounds using the apparatus and method described by Miller and Hunt in *J. Phys. Chem.*, vol. 49, 1945, p. 20. The values were obtained for combustion of each compound at 25 C, under an initial pressure of 30 atm of oxygen, by reactions producing liquid water, gaseous CO_2, and gaseous nitrogen.

3 The Calculated Performance of Hydrocarbon-White Fuming Nitric Acid Propellants at High Chamber Pressures, by C. H. Trent and M. J. Zucrow, Purdue University, March 1949, *PUR-6-M*.

The values of specific impulse for heptane, octane, decane, and eicosane oxidized by white fuming nitric acid have been calculated at chamber pressures ranging from 300 to 2058 psia. The effects of varying the C/H ratio of the fuel combustion pressure, and the oxidizer-to-fuel ratio on the specific impulse and on the temperature of combustion were determined. The performance of any of the four saturated hydrocarbons studied can be represented by average values. Raising the combustion pressure from 300 to 2058 psia increases the specific impulse by 20.9 per cent. The corresponding increase in the characteristic velocity is only 1.83 per cent while the increase in the value of the thrust coefficient is 18.43 per cent.

4 Some Thermodynamic Properties of the Nitroparaffins, by D. E. Holcomb, C. L. Dorsey, Jr., and L. H. Going, Purdue University, *Ind. Eng. Chem.*, vol. 41, no. 8, pp. 2788, Aug. 1949, *PUR-5-M-P*.

Heats of combustion and latent heats of vaporization of several straight-chain nitroparaffins were determined experimentally. Resulting values were used to test the accuracy of three methods of predicting heats of combustion of organic compounds from a knowledge of the chemical structure of the molecules. All three methods gave values accurate to within one per cent. Equation was developed which correlates heats of combustion of all the nitroparaffin samples for which data are available with an average deviation of two per cent. Conclusions of other investigators that heats of explosion and explosive powers of pure chemical compounds are related to the oxygen balance of the molecules were verified and extended.

5 1,3-Dinitropropane, by J. P. Kipersky, H. B. Hass, and D. E. Holcomb, Purdue University, *J. Amer. Chem. Soc.*, vol. 71, no. 2, pp. 516, Feb. 1949, *PUR-8-P*.

Propylene diiodide reacts with silver nitrate in ether at room temperature; 1,3-dinitropropane is obtained. Physical properties of latter are given.

6 The Thermodynamics of Combustion Gases; Temperature of Acetylene-Air Flames, by R. W. Smith, J. Manton, and S. R. Brinkley, Jr., Bureau of Mines, May 1954, *BUM-10-R*.

The thermodynamic properties of the products of combustion of acetylene-air flames are presented. The composition at thermodynamic equilibrium of the combustion products are given for temperatures and pressures as follows: $T(°\text{ K}) = 1400\text{-}[200]\text{-}2800$; $P(\text{atm}) = 0.01, 0.05, 0.10, 0.5, 1.0$. The results are presented in table form for various values of fuel-air ratio.

IV Combustion Phenomena

A Ignition

1 Effects of Several Variables Upon the Ignition Lag of Hypergolic Fuels Oxidized by Nitric Acid, by S. V. Gunn, Purdue University, *J. Amer. Chem. Soc.*, vol. 22 , no. 1, pp. 33–38, Jan. 1952, *PUR-17-P-R-M*.

A method is described for measuring the ignition lag of self-ignition (hypergolic) bipropellant combinations. Ignition lag data are reported for combinations of nitric acid with aniline, furfuryl alcohol, and mixtures of aniline and furfuryl alcohol. The ignition lags ranged from about 10 to about 400 millisec, depending upon such variables as temperature, acid composition, fuel composition, and metallic additives.

2 The Problem of Ignition, by G. von Elbe, Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 13–20, 1953, *BUM-8-P*.

This is a survey paper presented at the Fourth Symposium (International) on Combustion. Ignition by electric sparks and heated bodies are considered. The concepts of minimum ignition energy and quenching distance are discussed, and a simplified theory of minimum ignition energy is presented.

3 The Ignition of Fuel Droplets Descending Through an Oxidizing Atmosphere, by H. L. Wood and D. A. Charvonia, Purdue University, JET PROPULSION, vol. 24, no. 3, pp. 162–165, May 1954, *PUR-25-P*.

Ignition studies with three organic fuels, triethylamine, allylamine, and cyclohexene as they descend in single droplets through the decomposition vapors of white fuming nitric acid are discussed. The pertinent parameters varied were acid vapor temperature (350 to 550 C), fuel temperature (10 to 70 C), and fuel-drop diameter (2.6 to 4.2 mm). Theoretical approaches to explain the observed ignition delays have not been successful.

4 Effect of Initial Temperature on Minimum Spark-Ignition Energy, by I. R. King and H. F. Calcote, Experiment, Incorporated, *J. Chem. Phys.*, vol. 23, p. 2444, May 1955, *EXP-2-M*.

Data are presented concerning the effect of initial temperature on minimum spark ignition energy between −50 and +250 C for several hydrocarbons, propylene oxide, hydrogen, and carbon disulfide. The graph of the minimum spark ignition energy vs. equivalence ratio shows that the equivalence ratio at which the minimum in the ignition-energy curve occurs moves toward leaner mixtures and extends over a broader range of equivalence ratios as the initial temperature is increased. An equivalent shift in the maximum burning velocity curve with increasing initial temperature was also observed. The minimum spark ignition energy for stoichiometric mixtures with air of a number of fuels is summarized at 0, 25, and 100 C.

B Flame Propagation Rate

(a) *Laminar*

1 Equilibrium Atom and Free Radical Concentrations in Carbon Monoxide Flames and Correlation with Burning Velocities, by C. Tanford and R. N. Pease, Princeton University, *J. Chem. Phys.*, vol. 15, no. 7, pp. 413–433, July 1947, *PR-32-P*.

Calculations have been made of equilibrium concentrations of hydroxyl radicals and of hydrogen and oxygen atoms in moist carbon monoxide flames. Comparison with burning velocities, measured by Jahn by the Bunsen burner method, reveals a close correlation between observed burning velocities and such calculated hydrogen atom concentrations. Only a slight correlation exists with hydroxyl radical concentrations and none at all with calculated oxygen atom concentrations. A theoretical basis for these observations will be presented in a subsequent paper.

2 Theory of Burning Velocity. II. The Square Root Law for Burning Velocity, by C. Tanford and R. N. Pease, Princeton University, *J. Chem. Phys.*, vol. 15, no. 12, pp. 861–865, Dec. 1947, *PR-33-P*.

Previous papers by the authors having

suggested that the diffusion of active particles (chiefly hydrogen atoms) from the flame front is the controlling factor in combustion in Bunsen-type burners, an equation for burning velocity based on such a concept is derived. This equation shows that the burning velocity should be proportional to the square root of an expression in which the most important factor is the sum of the products p_iD_i for all effective atoms or free radicals, p_i being the concentration of an atom or radical at the flame front, and D_i its coefficient of diffusion into cold, unburnt gas. The burning velocity equation is applied to the combustion of carbon monoxide and hydrogen; excellent agreement between calculated and experimental values of the burning velocity is obtained. The equation is also used to account for the effect of pressure upon burning velocity.

3 Burning Velocities of Butadiene-1,3 with Nitrogen-Oxygen and Helium-Oxygen Mixtures, by E. J. Badin, J. G. Stuart, and R. N. Pease, Princeton University, *J. Chem. Phys.*, vol. 17, no. 3, pp. 314–316, March 1949, *Pr-25-P*.

Burning velocities of nitrogen-oxygen-butadiene-1,3 and helium-oxygen-butadiene-1,3 have been measured at atmospheric and reduced pressures. At atmospheric pressure the ratio of 3.7:1 for the maximum burning velocities was obtained for helium compared to nitrogen as the inert gas. Reduction of pressure caused an increase then a decrease in burning velocity for helium-oxygen-butadiene-1,3. The maximum value of the burning velocity occurred at 300 mm pressure. Calculations of the equilibrium concentrations of H, O, and OH for the gas mixtures used have been made. Assuming that the controlling factor in the burning velocity is the back-diffusion of H-atoms, good agreement between calculated and experimental burning velocity ratios is obtained.

4 Flame Propagation Studies, by G. H. Markstein, Cornell Aeronautical Laboratory, *Res. Rev.*, pp. 8–14, May 1950, *CAL-51-P*.

A general discussion of flame propagation is presented. Particular emphasis is placed on the mutual interaction of flame propagation and flow disturbances. Experiments performed at the Cornell Aeronautical Laboratory concerning investigations of flame structure are described.

5 The Effect of Water on the Burning Velocities of Cyanogen-Oxygen-Argon Mixtures, by R. N. Pease and R. S. Brokaw, Princeton University, *J. Amer. Chem. Soc.*, vol. 75, no. 6, pp. 1454–1457, June 1953, *PR-38-P*.

Burning velocities have been determined for cyanogen-oxygen-argon mixtures containing varying amounts of moisture. The effect of water is explainable on the basis of the Tanford-Pease theory of flame speeds. Experiments with heavy water suggest that the hydroxyl radical is more important than the hydrogen atom in determining the rate of flame propagation.

6 Current Theoretical Concepts of Steady State Flame Propagation, by M. W. Evans, Princeton University, *Chem. Rev.*, vol. 15, no. 3, pp. 363–429, Dec. 1952 *PR-37-P-R*.

The basic laws and equations which govern the behavior of flames together with the numerous modifications, assumptions, and approximations which are necessary to transform the basic equations into a form capable of being treated are presented. In addition, the current models and methods of attack are considered.

7 Burning Velocities of Methane with Nitrogen-Oxygen, Argon-Oxygen, and Helium-Oxygen Mixtures, by W. H. Clingman, R. S. Brokaw, and R. N. Pease, Princeton University, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 310–313, 1953, *PR-47-P*.

Burning velocities at one atmosphere and 25 C have been determined for methane in nitrogen-oxygen, argon-oxygen, and helium-oxygen mixtures. Results are correlated with values calculated by means of the Tanford-Pease theory. Experimental burning velocity ratios for the nitrogen-argon-helium case at 10 per cent methane are 0.43:1:1.417. Calculated values are 0.359:1:1.296. A modified Tanford-Pease theory gives 0.373:1:1.392.

8 Burning Velocity Measurements in a Spherical Vessel with Central Ignition, by J. Manton, G. von Elbe, and B. Lewis, Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 385–363, 1953, *BUM-5-P*.

Burning velocities for stoichiometric mixtures of propane-air, methane-air, and ethylene-air at one atmosphere in a spherical vessel show good agreement with those values obtained with a slot burner. Independent checks on burning velocity using experimental data show the various methods of calculation to be consistent. The theory of flame propagation in a spherical vessel is presented, and the advantages and disadvantages of this method of burning velocity measurements are discussed.

9 Burning Velocity Measurements on Slot Burners: Comparison with Cylindrical Burner Determination, by J. M. Singer, Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 352–358, 1953, *BUM-6-P*.

Analysis and comparison of Bunsen flames from both cylindrical and slot burners demonstrate that the use of the truncated cone method with slot burners is justified by the experimentally observed constancy of burning velocity; slot burners of different dimensions give consistent results, provided the ratio of the long side to the short side is greater than 3 and quenching and penetrating distances are avoided; a somewhat lower burning velocity results when slot burners rather than cylindrical burners are used, owing to removal of the effect of combustion surface curvature; the agreement of burning velocities determined by the spherical bomb and the present method is within experimental error.

10 Study of Pressure Dependence of Burning Velocity by the Spherical Vessel Method, by J. Manton and B. B. Milliken, Bureau of Mines, presented at the Gas Dynamics Symposium, Aug. 1955, *BUM-12-P*.

Burning velocity measurements over the pressure range from 1.5 to $^1/_{25}$ atm showed that pressure dependence is variable and apparently a function of burning velocity. Burning velocities below 50 cm/sec varied inversely with pressure. In the 50- to 100-cm/sec range, burning velocity was almost constant with pressure; from 100 cm/sec upward, burning velocity increased with pressure. Observations indicated that all burning velocities must approach a constant value at very low pressures.

11 Burning Velocities by the Bunsen Burner Method. I. Hydrocarbon-Oxygen Mixtures at One Atmosphere. II. Hydrocarbon-Air Mixtures at Subatmospheric Pressures, by J. M. Singer, J. Grumer, and E. B. Cook, Bureau of Mines, presented at the Gas Dynamics Symposium, Aug. 1955, *BUM-13-P*.

The Bunsen burner technique of measuring burning velocity was applied to the following fast burning mixtures: CH_4-O, C_2H_6-O, and C_3H_8-O at atmospheric pressure. Mixtures of CH_4-air, C_3H_8-air, and ethylene-air were investigated by the same technique at subatmospheric pressure. The potentialities of the Bunsen burner method were re-examined; the disadvantages inherent in all burner methods are discussed.

12 Burning Velocities of Hydrogen-Air Flames, by H. Burwasser and R. N. Pease, Princeton University, submitted to *J. Amer. Chem. Soc.*, July 1955, *PR-57-P*.

Burning velocities of hydrogen-air mixtures were measured by the Bunsen burner method. A modified angle technique applied to the dark outer edge of the shadow cone was used in calculating the burning velocities. An attempt was made to correlate the experimental result with approximate diffusion and thermal theories of flame propagation. Diffusion theory predicts a maximum in burning velocity at a leaner H composition than is observed experimentally, whereas thermal theory predicts a maximum at a richer composition (29 vs. 42 vs. 55 per cent H_2).

13 Equations of a Simple Flame Solved by Successive Approximations to the Solution of an Integral Equation. I. First Order Reaction. II. Second Order Reaction. III. A Simple Ideal Non-Branching Chain Reaction Flame. IV. Simple Ideal Flame Model Suggested by the HBR Flame, by G. Klein, University of Wisconsin, July 1955, *WIS-1-R*.

The various cases are treated by solving the flame equations in integral for using a method of successive approximation in the integrands. In these models it appears that radical diffusion cannot be controlling.

14 Equations of a Simple Flame Solved by Successive Approximations to the Solution of an Integral Equation. Part V. A Simple Ideal Branching Chain Reaction Flame, by G. Klein, University of Wisconsin, Aug. 1955, *WIS-1-R Part V*.

The equations of a one-dimensional stationary flame $A \leftrightarrows 2B$ and $A+B \leftrightarrows B+C$ are solved by a perturbation method. The unperturbed equations are those of the reduced problem in which (a) the first reaction is in equilibrium, and (b) the diffusion constant has the speciel value unity; the reduced problem is solved by successive approximations to the solution of an integral equation. The component B, corresponding to a free radical in a real flame, occurs in the cold temperature region overwhelmingly by diffusion.

15 Critical Considerations in the Measurement of Burning Velocities of Bunsen Burner Flames and Interpretation of the Pressure Effect, by W. H. Clingman and R. N. Pease, Princeton University, submitted to *J. Amer. Chem. Soc.* Nov. 1955, *PR-59-P*.

An investigation was conducted of the burning velocity of CH_4 under various conditions. Experimental results were compared with the Semenov theory and a modified form of the Tanford-Pease theory of flame propagation. An improved Bunsen burner method of determining the burning velocity is presented in which it is determined for each flame observed whether there is a region of the flame cone over which the flame velocity is constant. This method yields burning velocity values which are independent of flow rate and burner diameter. The Tanford-Pease theory qualitatively predicted the results.

16 A Comparison of the Burning Velocities of Methane and Heavy Methane in Nitrogen and Argon "Airs" at Atmospheric Pressure, by W. H. Clingman and R. N. Pease, Princeton University, submitted to *J. Amer. Chem. Soc.*, Nov. 1955, *PR-60-P*.

The burning velocities of CH_4 and CD_4 were measured at atmospheric pressure and in both N and A to determine whether diffusion or heat conduction is more important in flame propagation. The ratio of the burning velocity of a mixture with CH_4 to that of a mixture with CD_4 of the same composition was always greater than 1 and increased with increasing concentration of

fuel. A proposal was made that the burning velocities of CH_4 and CD_4 be compared at 1 atm and varying compositions. The results of the study favored a diffusion mechanism.

17 Derivation of the Flame Equations, Their Transformation and a Suggested Method of Their Solution, by G. Klein, University of Wisconsin, Nov. 1955, *WIS-2-R.*

The equations of a one-dimensional flame under stationary conditions are deduced from the general equations of a gas mixture, and their boundary conditions are discussed. These equations are transformed in order that a perturbation method of successive approximations can be used for their solution. This procedure divides the system of equations into (a) two principal equations which are formally analogous to the equations of a unimolecular reaction flame *A B*, and (b) subsidiary equations which contain the remaining physical relations.

(*b*) *Turbulent*

1 One-Dimensionalized Aerothermodynamic Theory of Turbulent Flame Propagation in Flame Tubes, Part I, by J. K. L. MacDonald, New York University, Nov. 1947, *NYU-19-R.*

General one-dimensional aerothermodynamical equations and methods for solving them are obtained in forms suitable for use in connection with eddy-turbulent flame propagation in flame tubes. Such flames resemble those in pulsejets and are being studied partly to provide data on combustion parameters for use in the theoretical treatment of pulsejets. Solutions obtained by use of characteristics and finite differences are compared with explicit analytical solutions of approximating linear differential equations. Good agreement is found between the solutions for typical cases. The analytical solutions are general enough to cover almost any practical case.

2 One-Dimensionalized Aerothermodynamic Theory of Turbulent Flame Propagation in Flame Tubes, Part II, by J. K. L. MacDonald and J. L. Neuringer, New York University, July 1948, *NYU-4-M.*

A set of formulas is obtained for the flame motions in a flame tube of the type described in *NYU-19-R.* The present results refer to new initial conditions suggested by recent experimental work, and are presented for use in the analysis of recent and pending observations.

3 A Preliminary Study of Flames in Tubes Containing Grids, by M. W. Evans, M. D. Scheer, and L. J. Schoen, New York University, Dec. 1947, *NYU-18-R.*

A preliminary experimental study of the propagation of flames in tubes with grids is reported. The grids are found to produce flames of high velocity. The influence of grid design, tube length, and mixture composition on the shape of the flame front position time curve of the high velocity flame is examined. These flames are believed to resemble those in a pulsejet, and it is thought that this information, particularly when used in connection with pressure, temperature, and stream velocity data yet to be obtained, will be useful in understanding the pulsejet.

4 A Study of High Velocity Flames Developed by Grids in Tubes: The Role of Turbulence in Combustion Processes, by M. W. Evans, L. J. Schoen, M. D. Scheer, and E. L. Miller, New York University, Third Symposium on Combustion, Flame, and Explosion Phenomena, Baltimore, Sept. 1948, pp. 168–175, *NYU-17-R-P*$_1$. **Augmented Flames in Half-Open Tubes,** by M. W. Evans, M. D. Scheer, L. J. Schoen, and E. L. Miller, New York University, *J. Appl. Phys.*, vol. 21, no. 1, pp. 44–48, Jan. 1950, *NYU-17-P.*

High velocity flames in half-open tubes produced by placing a grid augmenter in the path of an advancing flame are described. High speed schlieren motion pictures and instantaneous pressure measurements are used to study flame structure and accompanying flow in the tube. It is found that the grid augmenter causes a mixing of burning and unburned gases, resulting in an increase in reaction surface. As a result the total amount of reaction per unit time per unit volume is increased, thus leading to the observed high velocities.

5 Flame Propagation Velocities of Air-Propane Mixtures in a Controlled Turbulence, by H. J. Buttner, F. W. Bowditch, and W. W. Floyd, Purdue University, *Texas J. Sci.*, vol. 1, no. 8, pp. 136–140, Sept. 1949, *PUR-9-P.*

Measured flows of air and propane were mixed and fed into a burner with a 0.422-in.-diam port in which a 0.086-in.-diam rod was rotated at controlled speeds to create turbulence. The flame was photographed, cone area measured, and propagation velocity deduced by the method of Gouy. With a 22:1 air-propane mixture flowing at 7.5 cu in./sec, propagation velocities vs. rpm were determined. At 7280 rpm, the velocity was 18.3 in. sec. Velocities for laminar flow (zero rod rpm) with 13:1 to 21:1 mixtures increased from 4 to 14.3 in./sec.

6 Studies on Turbulent Flames at the Bureau of Mines, by B. Karlovitz, Bureau of Mines; presented at the 12th Meeting of the BUMBLEBEE Propulsion Panel at the Applied Physics Laboratory, The Johns Hopkins University, 1952, *BUM-1-P.*

The concept of flame generated turbulence is discussed, and a relation between laminar and turbulent burning velocity is presented and compared with experimental results. Two electronic probe methods for the investigation of turbulence intensity in flames are described. A discussion of flame propagation across velocity gradients is presented.

7 Propagation of Turbulent Flames, by A. C. Scurlock and J. H. Grover, Atlantic Research Corporation, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 645–658, 1953, *ARC-1-P.*

A theory for propagation of turbulent flames is proposed which differs in many respects from previous concepts. Turbulence is assumed only to wrinkle and extend the flame area. The laminar flame velocity is thus assumed to remain constant and unaffected either by any increase in transport properties or by flame curvature.

An initially flat flame surface of infinite extent propagating through a flowing combustible mixture agitated by isotropic turbulence of given scale and intensity is considered. For this system a relation is obtained which expresses the ratio of turbulent flame area to initial area of the flat flame in terms of the mean-square displacement of a flame element from the flame front, $\overline{y^2}$, and the scale. As time passes and the initially flat flame is wrinkled by turbulence, three effects are of importance in determining the area of the wrinkled flame: (a) Eddy diffusion associated with turbulence in the unburned gases which tends to increase $\overline{y^2}$. (b) Propagation of flame into the unburned gases which tends to reduce $\overline{y^2}$. (c) Shear and eddy diffusion gradients due to the density decrease of the gases upon passage through the flame front which tends to increase $\overline{y^2}$.

Consideration is given to these three important effects acting independently and together on flames, and calculated results are compared with existing experimental data.

8 Open Turbulent Flames, by B. Karlovitz, Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 60–68, 1953, *BUM-9-P.*

The history of the elucidation of turbulent flame phenomena is reviewed. The understanding of the effects of small and large scale turbulence and the concept of flame generated turbulence are discussed. The phenomena and theory of the stability of turbulent flames are presented together with a discussion of the importance of the concept of a critical boundary velocity gradient.

9 Studies on Turbulent Flames. A. Flame Propagation Across Velocity Gradients. B. Turbulence Measurements in Flames, by B. Karlovitz, D. W. Denniston, Jr., D. H. Knapschaefer, and F. E. Wells, Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 613–620, 1953, *BUM-7-P.*

Theoretical consideration of the heat flow from the reaction zone of a laminar flame into the unburned explosive mixture shows that in the presence of a velocity gradient the heat flow is spread out over a larger volume of gas. thus decreasing the laminar burning velocity. Exact limits where propagation of the flame would cease cannot be predicted, but the calculated laminar burning velocity is reduced several-fold by the effect of velocity gradient at the experimentally observed limit. Two ionization probe techniques are described for measuring turbulence in or near flames, and experimental results obtained by both methods are given. For regions where the flame front is not too strongly distorted, average flame front fluctuation velocity agrees with the velocity of turbulent fluctuations.

10 The Burning Velocity of Turbulent Flames, by K. Wohl, L. Shore, H. Von Rosenberg, and C. W. Weil, University of Delaware, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 620–635, 1953, *DEL-2-P.*

Suggestions are made concerning the theory of turbulent flames by modification of the standard equations of turbulent burning velocity. The effect of approach stream turbulence involves amplification mechanisms, one of which may be called induction of flame created turbulence. Another effect is the tendency of the laminar flame front to become unstable with increasing fuel concentration for higher hydrocarbons. Experiments with flames burning from flameholders in ducts show that turbulent burning of this type of flames requires a high stream velocity, but not necessarily any approach stream turbulence.

11 Burning Velocity of Unconfined Turbulent Flames, by K. Wohl and L. Shore, University of Delaware, *Ind. Eng. Chem.*, vol. 47, p. 825, April 1955, *DEL-5-P.*

Theories of turbulent burning velocity are reviewed. The theory of Scurlock and Grover is discussed and it is shown that the scale of turbulence affects the turbulent burning velocity only as long as the steady state is not reached. An approximate version of the final differential equation for the turbulent burning velocity is given, which can be integrated in closed form. The equations following from this theory are compared with the equation given by Karlovitz, Denniston, and Wells and a modified version of it.

The average turbulent burning velocity of butane-air and methane-air flames burning from tubes in air at ordinary pressure was measured from the area of maximum luminosity, which is shown by chemical analysis to coincide with the one at which the oxygen concentration of the combustible mixture has dropped to 50 per cent. Intensity of approach stream turbulence has been varied independently of velocity with the help of screens.

The results for methane flames roughly agree with the predictions of Karlovitz, Denniston, and Wells for "passive" flame fronts. The burning velocity of rich butane flames is much larger than predicted; that of lean butane flames is much smaller. These effects are explained on the basis of the difference between the diffusivities of butane and oxygen. With increasing tube diameter, average turbulent burning velocity increases strongly because the flame front distortions traveling down the flame front have an increasing opportunity to grow. The peculiar shape of experimental curves confirms qualitatively Scurlock and Grover's theory of turbulence generating flames. The measured average turbulent burning velocity and the average base diameter of flame front distortions are not affected by the scale of approach turbulence within the experimental range.

C Flame Structure and Stability

1 Experimental Heat Release Determination for Flame Holding in Gaseous Mixtures, by H. J. Buttner, W. W. Floyd, and N. E. Parshall, Purdue University, Sept. 1948, *PUR-4-M.*

The burner developed for independently controlling that portion of mixture involved in the flameholding function made possible study of requirements for flameholding mixtures necessary for satisfactory burning in the main stream mixture and the determination of effects of variations in the physical and chemical condition of both the main mixture and the flameholding mixture upon the flameholding function. Main stream fuel-air ratio and velocity of flow determined the quantity of heat release necessary to maintain stable burning of an unconfined flame. Quantity of mixture required for the flameholding function serves as a relative indication of annulus heat release necessary to maintain stable burning in the main stream mixture. Flame propagation velocity within the unconfined main jet increased according to an exponential function of the main fluid stream velocity. Maximum flame propagation velocity occurs with main fluid stream fuel-air ratios slightly richer than stoichiometric.

2 On the Hydrodynamic Stability of Flame Fronts, by H. Einbinder, Cornell Aeronautical Laboratory, presented before the American Physical Society, Jan. 1949, *CAL-47-P.*

The hydrodynamic stability of a plane flame front is treated by discussing the behavior of a first-order infinitesimal disturbance of the main flow, in an analogy with the well-known stability treatments of laminar parallel flows. The fundamental differential equations are derived and the velocity and pressure perturbations found. A continuous main flow velocity distribution is unstable. Landau's work on this problem, employing a discontinuous velocity distribution, is discussed. It is shown that thermal processes must be included. To this end, the first-order perturbation equations, including thermal as well as hydrodynamical processes, are derived as the first step toward the solution of the stability problem for a plane flame front.

3 Cell Structure of Propane Flames Burning in Tubes, by G. H. Markstein, Cornell Aeronautical Laboratory, *J. Chem. Phys.*, vol. 17, no. 4, pp. 428–429, April 1949, *CAL-50-P.*

The appearance of a cellular flame structure in propane-air and propane-air-nitrogen flames at low flow velocities is reported.

4 Interaction of Flame Propagation and Flow Disturbances, by G. H. Markstein, Cornell Aeronautical Laboratory, Third Symposium on Combustion, Flame, and Explosion Phenomena, Williams and Wilkins, Baltimore, pp. 162–167, 1949, *CAL-58-P.*

In order to gain a better understanding of the mechanism of flame propagation in a turbulent gas, effects of periodical disturbances on stationary flame fronts were studied, and the results are presented. Phenomena related to the effects of disturbances on flame shape, such as influence of disturbances on blowoff stability and spontaneous oscillations of inverted flames, are also investigated; and several examples are briefly discussed.

5 Flame Holding Requirements for Stable Combustion of Gaseous Mixtures Flowing at High Velocities, by H. J. Buttner and R. C. Teasel, Purdue University, Aug. 1949, *PUR-12-M.*

The method used was the determination of limits of stable combustion in the main stream for various flameholder flow rates and fuel-air ratios. Required heat release was calculated from combination of flow rate and fuel-air ratio.

Conclusion was drawn that for a given burner and flameholder, the absolute value of the heat release required per unit of interface area decreases with increasing main stream velocities. Decrease is considerable as flow of main stream increases at the lower velocities, but, at higher velocities, heat release required for stable burning approaches a constant value.

6 Experimental and Theoretical Studies of Flame Front Stability, by G. H. Markstein, Cornell Aeronautical Laboratory, *J. Aero. Sci.*, vol. 18, pp. 199–209, March 1951, *CAL-53-P-R.*

Rich hydrocarbon flames burning in tubes were found to assume a cellular structure in the absence of turbulence in the approach stream. The effects of type of fuel, mixture composition, and pressure on the phenomenon have been studied. A first-order perturbation treatment of flame front stability gave results in qualitative agreement with experiment when the dependence of burning velocity on flame front curvature was taken into account.

7 Interaction of Flow Pulsations and Flame Propagations, by G. H. Markstein, Cornell Aeronautical Laboratory, *J. Aero. Sci.*, vol. 18, no. 6, pp. 428–429, June 1951, *CAL-37-M-P.*

Some qualitative preliminary results are presented in connection with studies of flame propagating from the open to closed end of straight tubes containing premixed combustible gas. Pressure oscillations accompanied by cellular flame structures were observed. The first-order perturbation theory of flame front stability is generalized to include the case of vibratory flame motion.

8 Non-Isotropic Propagation of Combustion Waves, by G. H. Markstein, Cornell Aeronautical Laboratory, *J. Chem. Phys.*, vol. 20, no. 6, pp. 1051–1052, June 1952, *CAL-54-P.*

A reply is made to a criticism of the author's treatment of combustion wave instability.

9 Flame Stability of Liquid-Vapor Oxygen Mixtures, by J. A. Browning and M. L. Thorpe, Dartmouth College, Feb. 1952, *DART-1-M.*

Flame stability curves for a variety of liquid fuels burned in oxygen have been determined under varying conditions of stream temperature, flame tube diameter, and flame tube length-to-diameter ratio. Insufficient heat has been added to vaporize the fuel completely; thus, both the liquid and vapor states of the fuel are present in the mixtures. Results show a marked similarity between these flames and their gaseous fuel counterparts, except at low stream temperatures and high fuel concentrations, when a large portion of the fuel remains in the liquid phase.

Benzene-oxygen flames appear to have the favorable nonoxidizing qualities inherent in acetylene flames, and have the ability to produce strong fusion welds in steel.

10 Flame Stability of Liquid-Vapor Air Mixtures, by J. A. Browning and M. L. Thorpe, Dartmouth College, Oct. 1952, *DART-2-M.*

The flame stability diagrams for mixtures with air of normal-heptane, iso-octane, and benzene burned in the open atmosphere above Bunsen tubes were determined under varying conditions of stream temperature and tube diameter. Results are nearly identical to those obtained for gaseous fuels except at low temperatures and high fuel concentrations when a portion of the fuel remains in the liquid phase.

The use of a short outer tube enclosing the base of an air-fuel flame serves as an efficient stabilizing device. Flow velocities through the Bunsen tube can be increased to very high values without danger of overheating the stabilization device.

11 Cellular Flame Structure and Vibratory Flame Movement in n-Butane–Methane Mixtures, by G. H. Markstein and L. M. Somers, Cornell Aeronautical Laboratory, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, 1953, pp. 527–535, *CAL-52-P.*

Cellular structure and vibratory flame movement studies with mixtures of n-butane and methane showed a shift of the transition from smooth flames to fully developed cell structure to richer mixtures than for a single higher hydrocarbon. Only oscillations of the fundamental organ-pipe frequency occurred in a 2-ft tube, and the maximum amplitudes of these oscillations were significantly larger in mixtures that burned with cellular flame structure than with others. In a 4-ft tube, excitation of the fundamental frequency was preceded by the first harmonic for mixtures burning with cellular flame structure. The amplitudes of these oscillations showed no correlation with cell structure.

12 Instability Phenomena in Combustion Waves, by G. H. Markstein, Cornell Aeronautical Laboratory, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 44–59, 1953, *CAL-57-P.*

Theory and experiment on stability phenomena in combustion waves are reviewed. Reference is made to cellular and polyhedral flames and to pressure and flow oscillations associated with combustion.

13 Some Properties of Rod-Stabilized Flames of Homogeneous Gas Mixtures, by G. C. Williams and C. W. Shipman, Massachusetts Institute of Technology, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 733–742, 1953, *MIT-3-P.*

A study is made of the flow patterns about transverse cylinders (0.1 to 0.5-in. diam) holding flames in an atmospheric stream of propane-air mixtures flowing through a 1-in. × 3-in. rectangular duct. From measurements of wall pressure and pressure distribution about the cylinder circumference, analysis of the gases sampled in the immediate wake of the flameholder, and observations by still and high speed motion picture schlieren photography, conclusions are presented regarding processes involved in the stabilization and blowoff of flames anchored on bluff objects.

14 A Slot Burner Method for Studying Combustion Wave Instability, by L. M. Somers and G. H. Markstein, Cornell Aero-

nautical Laboratory, *J. Chem. Phys.*, vol. 21, no. 5, p. 941, May 1953, *CAL-45-P*.

A discussion of the methods of quantitative study of combustion wave instability is presented. A slot burner setup is described which eliminates the shortcomings of the tube technique without accepting all the drawbacks of polyhedral flame studies.

15 Interaction of a Plane Flame Front With a Plane Sinusoidal Shear Wave, by G. H. Markstein, Cornell Aeronautical Laboratory, *J. Aero. Sci.*, vol. 20, no. 8, p. 581, Aug. 1953, *CAL-56-P*.

The problem of the normal intersection of a shear wave and a combustion wave is treated in a letter to the editor. Results are presented in terms of the amplitudes of velocity perturbations and flame front deflection relative to that of the upstream shear flow.

16 Lateral Blowoff of a Bunsen Flame, by M. L. Thorpe and J. A. Browning, Dartmouth College, *Ind. Eng. Chem.*, vol. 46, no. 10, pp. 2203–2205, Oct. 1954, *DART-5-P*.

Blowoff limits for Bunsen flames burning within a secondary stream of atmospheric air have been studied. Results obtained between certain limits of fuel-air ratio and secondary stream velocity show that high Bunsen tube stream velocities can maintain a stable flame. The presence of the Bunsen tube creates eddies within the secondary stream. Thus, this tube acts as a flameholder.

17 On the Stability of a Plane Flame Front in Oscillating Flow, by G. H. Markstein and W. Squire, Cornell Aeronautical Laboratory, *J. Acoust. Soc. Amer.*, vol. 27, no. 3 pp. 416–424, May 1955, *CAL-66-P*.

Recent experimental studies revealed a close connection between spontaneous excitation of organ-pipe oscillations by flames propagating in tubes and flame front instability characterized by cellular structure. On the basis of these observations a dominant mechanism of vibratory flame movement is proposed, consisting of two steps: (a) As a consequence of acceleration instability, the oscillation of the gas column alternatingly distorts and flattens the flame front, thus creating the observed vibration-induced cell structure. (b) The distortions of the flame front cause in turn periodic changes of flame surface area and therefore of burning rate. Spontaneous oscillations are excited if the phase relation between burning rate variation and pressure oscillation is favorable.

In this paper only the first step is analyzed. The linearized treatment yields stability limits in terms of dimensionless parameters representing amplitude and frequency of gas column oscillation and wavelength of flame front distortion. The properties of the flame front entering into the analysis are the ratio of densities of unburned and burned gases, the burning velocity of the plane flame front, and a characteristic length that determines its stability in the absence of oscillations. Results in qualitative agreement with experimental observations are derived.

18 Interaction Between Pressure Waves and Flame Fronts, by G. H. Markstein and D. Schwartz, Cornell Aeronautical Laboratory, JET PROPULSION, vol. 25, p. 174, 1955, *CAL-62-M*.

A shock tube method was developed for studying the effects of pressure wave disturbances on flame propagation. Preliminary results of the interaction phenomenon were obtained with oscillographic records of the pressure transients and schlieren high speed motion pictures. A pressure record obtained with air in a combustion chamber was compared with a pressure record obtained while burning a stoichiometric butane-air mixture in the chamber. A sequence of frames are shown from a schlieren motion picture of flame front pressure wave interaction in a stoichiometric butane-air mixture.

19 Studies of Ionization in Flames by Means of Langmuir Probes, by H. F. Calcote and I. R. King, Experiment, Incorporated, Fifth Combustion Symposium Volume, 1955, *EXP-1-P*.

The use of the Langmuir probe in studying ionization in flames is described with typical results and an interpretation of some of the experimental evidence to prove that ionization in the combustion zone is not due to contaminants. The arguments for this conclusion are: (a) Flames of some fuels do not contain ions. Were contaminants responsible, all flames would be expected to have ions present. (b) Flames at low temperatures have high ion concentrations such that it would require one mole per cent sodium impurity in the input gas to account for the observed concentration. (c) Ionization is concentrated in a very thin region comparable in thickness to the reaction zone. (d) Results at different pressures cannot be correlated by assuming thermal ionization of contaminants.

20 Cellular Slot Burner Flames, by G. H. Markstein and D. Schwartz, Cornell Aeronautical Laboratory, presented at the Gas Dynamics Symposium, Aug. 1955, *CAL-64-P*.

A slot burner method for investigating cellular flame structure was developed. Steady flames consisting of a single row of cells separated by straight and parallel ridges were obtained on the burner over fairly wide ranges of combustible mixture composition and flow rate. Rich butane-air mixtures were employed in this study. Streak camera records of nonsteady cellular flames were obtained. Within the range of equivalence ratios between 1.25 and 1.45, minimum cell width remained almost constant, with an indication of a shallow minimum of 0.31 cm at an equivalence ratio of 1.36; for richer mixtures, the cell width increased up to 0.060 cm for an equivalence ratio of 1.75.

21 Effect of Probe Size on Ion Concentration Measurements in Flames, by I. R. King and H. F. Calcote, Experiment, Incorporated, *J. Chem. Phys.*, vol. 23, p. 2203, 1955, *EXP-3-M*.

Further investigation disclosed that the measured value of positive ion concentration (N_+) was dependent on the size of the measuring probe. Data are presented to indicate that correction for probe size can be accomplished with the equation

$$N_1 \text{ (corrected)} = (r/l)\, N_+ \text{ (experimental)}$$

where r is the radius of the probe and l is the mean free path. Discrepancies in ion concentration with the addition of salt to the flame are now considered to result from probe size effects and not from cooling.

22 Boundary Layer Effects on Bluff-Body Flame Stabilizers, by P. T. Woo, Massachusetts Institute of Technology, Sept. 1955, *MIT-8-T*.

Experimental work is summarized on a study of the effect of boundary layer thickness on (a) flame stability corresponding to various rates of boundary layer withdrawal, and (b) molecular diffusion and wake gas composition. The studies suggest that boundary layer removal produces the following effects in the wake of bluff-body flame stabilizers: (a) the combustion reaction propagating into the free vortex layer is chilled by the cold gases in a thinned vortex layer; (b) the recirculation rate of hot combustion products into the immediate wake is reduced because of the narrowing of the wake; and (c) the difference in composition between the immediate wake and the approach stream increases.

D Flame Spectra and Radiation

1 Application of Spectrography to the Study of Reaction Mechanisms in Low Pressure Flames, Instrumentation and Preliminary Studies in the Ultraviolet, by G. H. Rothgery and J. T. Grey, Cornell Aeronautical Laboratory, Nov. 1948, *CAL-22-M*.

Report deals with the description and operation of the low pressure burner together with the accessory instrumentation plus the spectrographic equipment used at the Cornell Aeronautical Laboratory in studying combustion phenomena at low pressure. Spectrographic examination of stable flames, burning over a wide range of pressures and oxygen-fuel ratios, were made in the ultraviolet region of the spectrum with a Bausch and Lomb Littrow Spectrograph.

Preliminary results indicate that OH radical concentration may be related to the pressure through the relation, (OH) $\backsim A \log p$. The CH radical concentration in the flames exhibits a similar behavior. Extensive broadening of the reaction zone has been observed with reduction of pressure in the burner.

2 Spectroscopic Study of Combustion, Relative Intensity of OH, CH, and C_2 Bands in Methane Flames at Low Pressure, by G. H. Rothgery and J. T. Grey, Cornell Aeronautical Laboratory, March 1949, *CAL-24-M*.

The intensity of OH bands was found to be independent of mass flow and partial pressure of methane and to increase linearly with burner pressure up to about 25 mm, after which a gradual increase in slope occurred. The CH bands were also found to be independent of mass flow, to increase linearly with increasing partial pressure of methane and also with decreasing oxygen-fuel ratio, and to increase with burner pressure up to about 25 mm, at which point a gradual decrease in slope occurred. The fact that linear increases were observed for both the partial pressure of methane and oxygen-fuel ratio indicates that the spread of experimental parameters was insufficient to establish the dependence uniquely. The intensity of the C_2 bands was found to increase linearly with increasing partial pressure of methane and to increase with pressure up to a burner pressure of about 25 mm, at which point a gradual progressive decrease in the slope of the curve was observed. A correlation between the variations noted in the intensity vs. pressure curves for OH, CH, and C_2 bands and the mechanism of formation of CH radicals is suggested.

3 Isotope Effect in Hydrocarbon Flame Spectra, by G. M. Murphy and L. Schoen, New York University, *J. Chem. Phys.*, vol. 19, no. 3, pp. 380–381, March 1951, *NYU-9-P*.

The spectra of the low pressure flame of atomic oxygen and deuterated acetylene (C_2D_2) were photographed in the first and second orders of a Jarrell-Ash three-meter grating spectrograph. Comparison with the spectra of a normal acetylene flame recorded under similar conditions leads to an isotopic displacement in those bands caused by hydrogen-containing molecules from which it is theoretically possible to obtain information concerning the identity and structure of the emitter.

4 The Determination of the Temperature of Non-Luminous Flames by Radiation in the Near Infrared, by L. Bernath, H. N.

Powell, A. G. Robison, F. Welty, and K. Wohl, University of Delaware; conference of the Institution of Mechanical Engineers and The American Society of Mechanical Engineers, London, Sept. 11–13, 1951, *DEL-1-P.*

A two-wavelength method for the measurement of flame temperatures which does not require a high emissivity so that it can be employed in the nearest infrared is described. The temperature is obtained from the ratio of the two peaks of the water band system after the ratio of emissivities at those two wavelengths has been established. The method is applicable to any combustion process in which water vapor is produced. Data on infrared radiation and temperature of butane-air and hydrogen-air flames are presented and discussed.

5 Spectroscopic Study of Combustion, Summary Report, by G. H. Rothgery and J. T. Grey, Cornell Aeronautical Laboratory, Sept. 1951, *CAL-34-M.*

A study of combustion phenomena at low pressure has been made through a spectrographic examination of stable flames. A range of burner pressures and oxygen-fuel ratio has been investigated. The relative intensity of the OH, CH, and C_2 bands has been studied as a function of the combustion parameters, burner pressure, mass flow, oxygen-fuel ratio, and partial pressure of fuel.

A correlation between the variations found for the relative intensity of these bands as a function of pressure and a previously suggested mechanism of formation of CH radicals has been noted.

6 Vibrational Structure of the Hydrocarbon Flame Bands, by G. M. Murphy and L. Schoen, New York University, *J. Chem. Phys.*, vol. 19, no. 9, pp. 1214–1215, Sept. 1951, *NYU-23-P.*

A vibrational analysis of the hydrocarbon flame band system based on two active modes of vibration in the wavelength region 2500 to 4000 Å is presented.

7 Effect of Gas Temperature Gradients on Radiant Heat Transmission, by E. S. Cohen, Massachusetts Institute of Technology, July 1955, *MIT-7-T.*

An investigation to develop a technique for calculating radiant heat transmission in enclosures is summarized which makes allowance for temperature nonuniformities in the gas mass. The technique involves the evaluation of the emission from either a gas zone or a surface zone and the radiant interchange between any two of these zones while taking into account the absorption along every beam from one zone to another and the partial diffuse reflection of every beam to every surface. A numerical example was worked out for the case of a highly idealized furnace.

E Miscellaneous

1 Phenomena in Electrically and Acoustically Disturbed Bunsen Burner Flames, by M. L. Polanyi and G. H. Markstein, Cornell Aeronautical Laboratory, Sept. 1947, *CAL-3-M-R.*

The study of flame propagation under turbulent flow conditions by means of an indirect method is proposed, which comprises stroboscopic observation of Bunsen flames subjected to periodical disturbances of electric or acoustical nature. It is found that the disturbances act on the flame only in the region immediately above the burner port, creating wave-shaped distortions of the flame front which travel upward along the flame cone with a velocity equal to the velocity of gas flow, within experimental accuracy. While the distortions travel up, their amplitude increases gradually for moderate intensities of the disturbance; for large intensities an initial increase is followed abruptly by a decrease. The surface area of the distorted flame cones is found to be constant during the whole cycle and independent of the intensity of the disturbance. The significance of these observations for the theory of flame propagation in a turbulent medium is discussed.

Investigation of electrically disturbed flames led to the discovery of an increase of the blowoff limit of Bunsen flames under the influence of direct and alternating electrical fields.

2 Electrical Properties of Flames (Burner Flames in Longitudinal Electric Fields), by H. F. Calcote and R. N. Pease, Princeton University, *Ind. Eng. Chem.*, vol. 43, no. 12, pp. 2726–2731, Dec. 1951, *PR-6-M-P-R.*

A study of the effect of longitudinal electric fields on the blowoff limits, dead space, and flame pressure of Bunsen burner flames was undertaken to determine the nature of the effect and the significance of the abnormal concentrations of ions in flames.

The results indicate that the electric field has a strong influence on the flame stability, the direction depending on the field polarity. A mechanical model is presented which qualitatively explains most of the results. The change in flame pressure indicates that the product of the ion concentration in ions per cubic centimeter and the flame thickness in centimeters is approximately 10^{10}, in agreement with the value calculated for transverse electric fields. For high negative electric fields it is assumed that the electrons acquire sufficient energy to raise the gas to an excited state.

The large number of ions which must be present to produce these effects cannot be accounted for thermodynamically and are probably due to chemi-ionization, although they do not appear to play a significant role in the combustion process.

3 Influence of Wall Material on Combustion, by J. L. Beal, P. E. Erbe, and J. T. Grey, Cornell Aeronautical Laboratory, Sept. 1952, *CAL-40-M.*

The possible catalytic effect of various wall materials and surface conditions on the combustion of premixed fuel and air has been investigated in heavily insulated tubes of small internal diameter. In comparison with inconel, various metals and their respective oxides exhibited no appreciable difference. Silica, however, exhibited a positive effect. No significant effects could be traced to the internal surface condition of the tube.

4 Basic Flame Studies and Their Relationship to Welding Equipment, by M. L. Thorpe and J. A. Browning, Dartmouth College, *Welding J., Research Suppl.*, Oct. 1952, *DART-3-P.*

From an analysis of the known principles of flame stabilization, remedies are suggested that might eliminate continued burning of a fuel-air mixture after flashback has taken place in a welding torch. The use of benzene for welding and a test apparatus designed for a study of the simplest elements of a welding flame are briefly described.

5 The Existence and Stability of Simple One-Dimensional, Steady State Combustion Waves, by J. M. Richardson, U. S. Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 182–189, 1953, *BUM-4-P.*

The existence and stability of one-dimensional, steady-state combustion waves are analyzed for the case of a simplified model of a combustion wave using only one state variable. A simple analytical approximation is devised for the determination of the steady-state solution and its limits of existence. The nonplanar transient problem linearized in deviations from the one-dimensional steady state can be treated by an exact method. It is found that the one-dimensional steady state, when it exists, is always stable.

6 Quenching, Flash-Back, Blow-Off—Theory and Experiment, by K. Wohl, University of Delaware, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 68–89, 1953, *DEL-3-P.*

In a survey of theoretical and experimental data regarding the phenomena of quenching, flashback, and blowoff, existing theory and experiments are reviewed. A discussion of the relationship between quenching distance and dead space is presented. The limitations of the velocity gradient at the tube wall as the suitable parameter which is to be interpreted by theory is discussed with respect to the explanation of flashback and blowoff phenomena.

7 Heterogeneous Combustion of Gases in a Vortex System, by H. C. Hottel and R. A. Person, Massachusetts Institute of Technology, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 781–788, 1953, *MIT-4-P.*

A study of combustion in a simple type of three-dimensional vortex system which might produce significant recirculation for mixing in a regular pattern as opposed to the random turbulence in conventional high output combustion chambers is described. Cold flow investigations were utilized to determine the nature of the vortex flow. Hot flow tests were used in a comparison of the vortex system with other high output combustors in terms of heat release per unit volume, combustion efficiency, and pressure drop.

8 Selections From: AGARD Combustion Colloquium, by B. Karlovitz, B. Lewis, G. H. Markstein, A. C. Scurlock, J. H. Grover, and K. Wohl; Selected Combustion Problems, Fundamentals and Aeronautical Applications, Butterworths Scientific Publications, London, 1954, *PR-52-P.*

Contributions by Project SQUID authors to the Combustion Colloquium at Cambridge, England, in December 1953 which was sponsored by AGARD, NATO:

Karlovitz, B.
A Turbulent Flame Theory Derived from Experiments
Lewis, B.
Remarks on the Combustion Wave
Markstein, G. H.
Discussion on Turbulent Combustion
Scurlock, A. C., and Grover, J. H.
Experimental Studies on Turbulent Flames
Wohl, K.
Discussion on Turbulent Flames and Flame Spectroscopy

9 Effect of Fuel Droplets on Flame Stability, Flame Velocity, and Inflammability Limits, by J. A. Browning and W. G. Krall, Dartmouth College, Fifth Combustion Symposium Volume, 1955, *DART-4-P.*

The flame velocities, inflammability limits, and stability limits of mixtures of kerosene mist in air have been measured. The mist is composed of droplets of submicron diameter formed by the rapid condensation of the fuel vapor in cold air. The maximum laminar flame velocity and the lean limit of inflammability for the mist are equivalent to values obtained for a gaseous fuel counterpart. However, the rich limit is considerably higher than for the vapor, and the stability limits are wider.

10 Combustion of Droplets of Heavy Liquid Fuels, by H. C. Hottel, G. C. Williams, and H. C. Simpson, Massachusetts Institute of Technology, Fifth Combustion Symposium Volume, 1955, *MIT-6-P.*

Droplet burning was studied by project-

ing a stream of uniform droplets up into an electric furnace and allowing the droplets to follow their trajectories inside the furnace and out through the bottom of the furnace. The experiments showed that the combustion of pure hydrocarbon droplets takes place in two stages, preheat and vaporization. In the preheat region, heat is supplied by radiation for the furnace walls and by conduction from the hot ambient gases. In the vaporization region, the major heat source in single-droplet burning is the flame envelope surrounding the droplet. Heat is transferred to the droplet surface by conduction against the vaporizing fuel.

11 The Effect of Particle Size on the Combustion of Uniform Suspensions, by J. A. Browning, T. L. Tyler, and W. G. Krall, Dartmouth College; submitted, to *Ind. Eng. Chem.*, 1956, *DART-6-P.*

The lean limit of inflammability and the maximum pressure rise of nearly monodisperse clouds of Armowax particles in air were determined. The maximum pressure reached during the constant volume combustion of suspensions composed of particles ranging from 10 to 90μ was inversely proportional to particle size. A maximum air-fuel ratio of 58:1 was obtained for the lean limit of inflammability for 60μ particle suspensions. Larger and smaller particles had lean limits of lower air-fuel ratio with value of 25:1 for both 10 and 90μ sizes. No rich limit was evident within the range of mixture strengths tested.

12 Significance of Quenching by Ports in Burning-Velocity Measurements by Bunsen-Burner Methods, by J. M. Singer, J. Grumer, and E. B. Cook, Bureau of Mines, submitted to JET PROPULSION, March 1956, *BUM-14-P.*

Two photographs are presented of a 0.8 stoichiometric CH_4-air flame stabilized by a 1.0-cm-diam coil of 1-mm OD stainless steel tube, with and without water cooling; the coil was hot in the latter instance. The similar photographs show the absence of major quenching by the port over most of the flame. A similar experiment with stoichiometric CH_4-air flame resulted in an increase in flame height of about 4 to 5 per cent when the glowing hot coil was water cooled.

V Engines and Propulsive Systems

A General

1 Compressible Flow Through Reed Valves for Pulse Jet Engines, Part I. Hinged Reed Valves, by P. Torda, I. P. Villalba, and J. H. Brick, Polytechnic Institute of Brooklyn, June 1948, *PIB-14-R.*

An analysis of air inflow between hinged reeds is presented, and numerical examples are included for illustrative purposes. The analysis shows that when *slender* valves and tapered mass distribution are combined, nonundulating motion of the reeds occurs. Thus smooth inflow results and adverse transverse accelerations of the reeds are avoided.

2 Compressible Flow Through Reed Valves for Pulse Jet Engines, Part II. Clamped Reed Valves, by P. Torda, Polytechnic Institute of Brooklyn, July 1948, *PIB-17-R.*

A quasi one-dimensional analysis of the air inflow through clamped reed valves is presented. The analysis considers nonsteady, compressible, nonviscous flow with isentropic change of state during the period of valve opening. The use of the results for design purposes is discussed.

3 Approximate Theory of Compressible Air Inflow Through Reed Valves for Pulse Jet Engines, by P. Torda, Polytechnic Institute of Brooklyn, Sept. 1948, *PIB-18-R.*

An approximate theory of compressible air inflow between reed valves for pulsejet engines is presented. This method avoids the laborious calculations involved in an "exact" analysis, and it is well suited for use in the first stage of a new design. A comparison of the results obtained with those of the "exact" theory shows good qualitative agreement and also good quantitative agreement in the latter part of reed motion.

4 Influence of Earth's Gravitation on the Requirements of the Verticle Trajectory Rocket With Special Reference to Escape, by J. P. Sellers, Purdue University, *J. Amer. Rocket Soc.*, no. 75, pp. 126–142, 1948, *PUR-10-P.*

When the earth's gravitation is analyzed with respect to its influence on a rocket-propelled vehicle in a vertical trajectory, an analysis of the problem of reaching extreme altitudes is readily obtained. The first portion of the paper is a review of the fundamental dynamic considerations of the problem. Consideration of the principal differences between ideal and actual long range rockets and accounting for the variation of earth's gravitational attraction upon the rocket leads to a table of correction factors which can be used with the ideal rocket equations to give approximate actual rocket results.

5 Single-Flow Jet Engines, A Generalized Treatment, by J. V. Foa, Cornell Aeronautical Laboratory, *J. Amer. Rocket Soc.*, vol. 21, no. 5, 1951, pp. 115–126, *CAL-46-P-R.*

Generalized performance equations are obtained for single flow air breathing jet engines from entropy considerations. The analysis is simplified by the use of convenient parameters in the description of the modes of compression, combustion, and expansion. The generalized equations are applied to a few cases of current interest for the purpose of illustration.

6 Thrust and Drag, by R. C. Weatherston, Cornell Aeronautical Laboratory. *J. Amer. Rocket Soc.*, vol. 22, no. 6, 1952, pp. 343–344, *CAL-55-P.*

In a letter to the editor, an attempt is made to arrive at a standard and realistic definition of the available thrust of a jet engine.

B Air Breathing

1 Frequency Response of Pressure Pick-ups Required for Measurements on a Pulse Jet, by G. Rudinger, Cornell Aeronautical Laboratory, June 1947, *CAL-1-M-R.*

A theoretical pressure cycle of a pulsejet is analyzed by means of a Fourier series development and the conclusion is reached that uniform frequency response up to about 6 times the cycle frequency is the minimum requirement for a pressure pickup to obtain a reasonable recording of the wave form. By studying another more idealized cycle, it is shown that this result holds not only for the special cycle selected but also applies to a wide range of wave forms which may be expected to occur in modern pulsejets. The frequency response required is not specified in absolute values but in terms of the cycle frequency, which may have widely different values in different jets.

2 Preliminary Experimentation on the CAL 6" × 4" Pulse Jet, by J. G. Wilder, Cornell Aeronautical Laboratory, June 1947, *CAL-6-M.*

Various reed thicknesses, two reed materials, two lengths of combustion chambers, and various fuel injection systems were tested. Difficulties were encountered in the attainment of proper fuel-air mixing; this item was deemed critical for satisfactory operation. Thick reeds showed, generally, a longer life than thin ones; but the pulsejet was more difficult to start, and resonance was more easily upset when heavy reeds were used. Maximum thrusts for various configurations tested with the corresponding fuel flows, specific impulses, and frequencies (where observed) are tabulated. All fuel was injected from an external nozzle spraying downstream directly into the intake valve.

3 Suggested Forms of Air Duct Motors Utilizing Intermittent Combustion, Part I. Intermittent Jet Engines, Part II. Intermittent Combustion Turbines, by J. G. Logan, Jr., Cornell Aeronautical Laboratory, Feb. 1948, *CAL-15-M.*

This memorandum, which suggests modifications of existing intermittent combustion devices, is divided into two sections. The first considers theoretical and experimental studies of wave propagation in tubes and suggested modification of existing jet devices utilizing intermittent combustion. The second considers application of resonating principles to the combustion chambers of intermittent gas turbines.

4 Suggested Forms of Air Duct Motors Utilizing Intermittent Combustion, Part III. Modification of Combustion Cycle to Obtain Wave Reinforcement, by J. G. Logan, Jr., Cornell Aeronautical Laboratory, March 1948, *CAL-16-M.*

Modifications of the usual pulsejet cycle are proposed to obtain wave reinforcement. This may yield the extremely high efficiencies indicated for jets, produced by mechanical oscillations, at tube resonance frequencies. Possible designs of intermittent combustion engines operating on this cycle are suggested.

5 Suggested Forms for Air Duct Motors Utilizing Intermittent Combustion, Part IV. Intermittent Combustion Experiments, by J. Logan, Jr., and O. B. Finamore, Cornell Aeronautical Laboratory, April 1948, *CAL-20-M.*

Preliminary experiments conducted with valveless jet models have verified the theoretical conclusion that intermittent combustion processes could be sustained without the use of flapper valves which contribute to pulsejet inefficiency. These experiments, combined with previous observations of rough and explosive burning phenomena, indicate that this intermittent burning may be a very stable process in certain types of tubes.

6 The Aero-Resonator Power Plant of the V-1 Flying Bomb, by I. G. Diedrich, translated by A. Kahane, Princeton University, June 1948, *PR-4-M.*

General conclusions drawn from experimentation are as follows: Automatically operating spring flap valves are best suited for aero-resonators; however, more improvement is needed. Flow valves are of use where endurance and low useful thrust are important. Controlled Venetian-blind valves bring about an optimum increase of work. Best external shape of the aero-resonator is a compromise between optimum thermodynamic requirements of a combustion at the inside of the tube, the most favorable aerodynamic shape, and the shape and heat rigidity of the materials of the tube itself. Work on mixture formation basic requirements and basic types led to the conclusion that the steady internal mixture formation with the spoiler nozzle was most suitable. Fundamental requirements to be fulfilled were listed.

7 On Time and Space Functions of Heat Input Necessary to Produce, in a Tube, Waves of Density, Velocity, Pressure, Temperature, Momentum, and Periodic Thrust of Required Character, by H. J. Reissner, Polytechnic Institute of Brooklyn, July 1948, *PIB-12-M.*

A method to determine the time and space distribution of heat input that produce pressure functions yielding high thrust is presented for any time function of inflow

velocity and for any chosen flight speed conditions for a pulsejet. By means of an original choice of a mass wave along the whole length of the duct, a method is provided for the successive calculation of the time and space functions of the velocity, pressure, thrust, density, temperature, and heat input by means of simple quadratures.

8 Flame and Particle Motions in a Small Pulse Jet Engine, by P. Elias, New York University, July 1948, *NYU-21-R.*

The methods developed and the data obtained during fourteen months of laboratory experiments with several small pulsejet models are presented. A complete analysis of these data is not attempted but is to be included in later reports after further work is done. However, intrinsic flame speeds, i.e., flame speeds relative to the gases; and particle speeds, i.e., speeds of gas regions relative to the engine, are studied in some detail—valve action is correlated with these data. Many investigations were made in an effort to determine the location of the point where reignition occurs in the pulsejet engine, and the time of reignition was correlated with the operation of the valves. In this way a fairly complete description of the method of operation of a small pulsejet has been obtained. The concept of wave and flame propagation in the medium inside the pulsejet engine is considered and is used to give a semiquantitative explanation of some of the data.

9 Valveless Pulse Jet Investigations, Part I. Tests of Small Scale Models, by J. G. Logan, Jr., Cornell Aeronautical Laboratory, May 1949, *CAL-27-M.*

The results of an investigation of small valveless intermittent engines are described. These experiments were undertaken to determine if thrust and specific impulse values were appreciably affected by changes in fuel, methods of fuel injection, and duct geometry. The tests appear to confirm the expectation that high specific impulse values are obtainable with valveless engines. Mean values of approximately 2200 sec were obtained in the tests. The experiments indicate, also, that an optimum configuration exists for each particular fuel and method of fuel injection.

10. An Experimental Investigation of the Effect of Inlet Ducts on the Performance Characteristics of a Pulse Jet, by J. G. Wilder, Jr., Cornell Aeronautical Laboratory, July 1949, *CAL-29-M.*

Preliminary experimentation (using an 8-in. McDonnell pulsejet and inlet ducts varying in length from $1\frac{1}{2}$ to 6 ft) indicates a serious loss in thrust due to the addition of an inlet duct. The thrust does not always decrease with increasing duct length, however; indeed, there exist regions where an increase in duct length actually results in a gain in thrust for a given fuel flow. The maximum thrust obtainable with a given inlet duct is always less than the maximum thrust obtainable without an inlet duct for the configurations tested.

11 An Evaluation of the Potential Merits of Ducted Pulse Jets, by G. Rudinger, Cornell Aeronautical Laboratory, Oct. 1949, *CAL-32-M.*

A ducted pulsejet is a conventional pulsejet completely submerged in a surrounding duct, thus permitting operation at flight velocities which are so high that a pulsejet alone would not function. An analysis of such a power plant is presented in which the nonsteady phenomena are replaced by "effective" steady state conditions, and certain other simplifying assumptions are introduced. An analysis of the ramjet based on similar assumptions is also carried out. It is concluded that the ducted pulsejet should have a definite field of application in the subsonic range of flight velocities and possibly even up to low supersonic velocities, but any final decision on the best power plant for a specific application will also depend on additional considerations not treated here; i.e., drag or the relative importance of engine size vs. fuel consumption.

12 Effects of Cavity Resonators Coupled to Pulse Jet Engine Combustion Chambers, by J. Lemelson, New York University, August 1951, *NYU-13-M.*

Tubes of various diameters and lengths were attached to the combustion chamber of a dynajet engine. Thrust and fuel flow were measured for various configurations. It is shown that both thrust and fuel flow are markedly affected by the phase relation between the gas flow in the pulsejet engine and that in the tube. A suggestion is made to use a resonant cavity with ram air.

13 On the Performance Analysis of the Ducted Pulse Jet, by G. Rudinger, Cornell Aeronautical Laboratory, Oct. 1951, *CAL-36-M-P.* (See also: "A Problem Arising in the Performance Analysis of a Ducted Pulsejet," by G. Rudinger, Proceedings of the First National Congress of Applied Mechanics, ASME.)

Ducting of a pulsejet is a means to keep the engine operating at flight Mach numbers at which unducted conventional engines would not operate. It also allows the primary engine to take advantage of the possible ram precompression which is not utilized in the case of conventional pulsejets. Since no methods are available to analyze in detail the periodic flow phenomena that occur in engines of this type, some approximate method of performance calculation is required. Depending on the shroud configuration, mixing of the pulsejet exhaust with the remaining shroud flow may or may not take place. In the latter case, methods of analysis developed for single-flow engines may be applied; while in the former, only the equivalent steady flow approximation appears to be feasible at the present time. Estimates are derived for the magnitude of the flow pulsations in the shroud; and on the basis of this, a discussion of the equivalent steady flow approximation is presented. Unfortunately, it is found that only a rough estimate of the potential engine performance can be made. However, from the performance computed for various conditions, it is possible to draw conclusions about the merits of various configurations.

14 Report on Full Scale Pulse Jet Testing, by J. H. Hett, New York University, Nov. 1951, *NYU-12-M.*

A P. J. 31 pulsejet engine was mounted on a trailer and fired statically. An instrument trailer was built having 16 channels for information on cathode-ray tubes which were viewed by four drum cameras. Tests were made of the flame flow pattern in the engine using windows and a strip camera, and simultaneous determinations were made of valve position. To measure instantaneous pressures and instantaneous flame temperatures, special instruments were developed and mounted on the P. J. 31. Experiments were also made with instantaneous liquid flowmeters employing thermistors. Other experiments were performed with pulsating manometer systems. The project ended before simultaneous measures of all parameters could be obtained.

15 Summary Report on Valveless Pulse-Jet Investigation, by J. G. Logan, Jr., Cornell Aeronautical Laboratory, Oct. 1951, *CAL-42-M-P.*

The investigations conducted at Cornell Aeronautical Laboratory with valveless pulsejet engines from October 1948 to September 1951 and the whirling arm tests of 6-in. valveless pulsejets conducted at the Chesapeake Bay Annex of the Naval Research Laboratory between January 1951 and September 1951 are described. A summary of this report has been published in *Research Reviews*, pp. 5–10, Dec. 1951.

16 Theoretical and Experimental Investigation of the Feasibility of the Intermittent Ram-Jet Engine, Parts I and II, by A. Kahane, A. A. Marino, C. W. Messinger, Jr., and H. J. Shafer, Princeton University, August 1952, *PR-45-R.*

Theoretical and experimental investigations of the possibilities of an intermittent ramjet engine were made. Theoretical studies were made of several possible modes of intermittent combustion, gas dynamic cycle of the engine, and problem of diffuser and nozzle design. Performance theory of intermittent jet engines was developed, and specific impulse calculations of the intermittent ramjet were made for possible modes of combustion. Experimental investigations of the intermittent combustion process in a flowing gas in a constant area tube were made. Synchronized high speed motion picture and transient pressure studies were used to determine the mode of the combustion process occurring. Transient pressure rise measurements were made over a range of combustion chamber Mach numbers and fuel flows. Performance tests of a subsonic configuration at 0.5 Mach number were also made.

C Rockets

1 Fundamental Problems in Rocket Research, M. Summerfield, Princeton University, *J. Amer. Rocket Soc.*, no. 81, pp. 79–98, June 1950, *PR-26-P-R.*

Various problems that have arisen in connection with recent advances of rocket technology are discussed, and indications of directions in which solutions might be found are presented. The topics discussed are concerned with combustion, heat transfer, transport properties, and flow through exhaust nozzles. A comprehensive bibliography is presented.

2 Application of White Fuming Nitric Acid and Jet Engine Fuel (AN-F-58) as Rocket Propellants, by M. J. Zucrow and C. F. Warner, Purdue University, *J. Amer. Rocket Soc.*, no. 82, pp. 139–150, Sept. 1950, *PUR-16-P.*

White fuming nitric acid (WFNA) and hydrocarbon fuel are analyzed in terms of rocket propellants; both are liquids, readily available, inexpensive, and have satisfactory freezing points; calculated performance parameters for WFNA-hydrocarbon propellants; ignition; cooling of rocket motor; film cooling.

3 A Theory of Unstable Combustion in Liquid Propellant Rocket Systems by M. Summerfield, Princeton University, *J. Amer. Rocket Soc.*, vol. 21, no. 5, pp. 108–114, 1951, *PR-43-R-P.*

On the basis of a hypothesis that low frequency oscillations ("chugging) sometimes observed in liquid propellant rocket engines are the result of oscillatory propellant flow induced by a combustion time lag, condition for the suppression of such oscillations are derived. It is found that stability can be achieved by increases in the length of feed line, the velocity of the propellant in the feed line, the ratio of feed pressure to chamber pressure, and the ratio of chamber volume to nozzle area. Equations are given for the frequencies of oscillation. Examination of the equation for stability indicates that self-igniting propellant combinations are likely to be more stable than non-self-igniting systems.

4 Experimental Performance of WFNA-JP-3 Rocket Motors at Different Combustion Pressures, by M. J. Zucrow and C. M. Beighley, Purdue University, *J. Amer. Rocket Soc.*, vol. 22, no. 6, pp. 323–330, June 1952, *PUR-19-P.*

The performance and heat transfer rates for 500-lb thrust, $L^* = 100$ in., rocket motors were determined experimentally as a function

of mixture ratio at 300-, 500-, and 700-psia combustion pressures. In all cases the propellants used were white fuming nitric acid (WFNA) and jet engine fuel (JP-3). The maximum values of specific impulse were obtained at a mixture ratio of 4.5 and the values were 222, 235, and 246 for 300-, 500-, and 700-psia combustion pressure, respectively. Raising the combustion pressure from 300 to 700 psia increased the over-all heat transfer for the thrust cylinder from 1.3 to 2.3 Btu per sq in. per sec and that for the nozzle from 2.8 to 6.0 Btu per sq in. per sec.

VI Instrumentation

A Temperature Measurement

1 The Measurement of Gas Temperature, Part I, by M. Carbon, R. J. Albert, and G. A. Hawkins, Purdue University, May 1947, *PUR-1-M*.

This report covers the following topics: (a) The measurement of gas temperatures for high velocity flow; (b) brief abstracts of articles available at Purdue University on the measurement of gas temperatures for high velocity flow; (c) list of technical references which refer to the general subject of gas temperature measurement.

2 The Measurement of Gas Temperature, Part II, by M. Carbon, R. J. Albert, and G. A. Hawkins, Purdue University, May 1947, *PUR-2-M*.

This report covers the following specific items: the design and construction of apparatus for detecting, amplifying, and recording the voltage generated by a thermocouple operating under transient conditions; and thermocouple welding techniques.

3 Report of Conference on the Measurement of Temperatures of Pulsating Burning Gases, by J. H. Hett, New York University, April 1948, *NYU-2-M*.

Contains seven papers dealing with various methods of temperature measurements:

MacDonald, J. K. L.
Some Fundamental Aspects of Theories of Thermal Radiation

Strong, H. M.
The Measurement of Temperature by Sodium Line Reversal in Complex Flame Structures

Bundy, F. P.
The Theoretical Shapes and Intensities of Sodium Lines From Complex Flames

Hett, J. H.
Apparatus for Radiation of Temperature Measurements in Pulse Jets

Wolfe, C. M.
Application of a Lead Sulphide (PbS) Cell to the Measurement of Gas Temperatures in the Combustion Chamber and Tailpipe of an Aeroresonator

Bundy, F. P.
Effect of Temperature Zones on the Measurement of Temperature by the Absolute Radiation Method in Which the Optical Depth Is Determined by L vs. 2L Method

Sanderson, J. A., Curcia, J. A., and Estes, D. V.
Photoelectric Pyrometer and Bolometric Probes for the Measurement of Flame Temperatures.

4 Surface Temperature Determination by X-Ray Diffraction Technique, by A. Bender and I. Fankuchen, Polytechnic Institute of Brooklyn, June 1948, *PIB-5-M*.

Experiments were based on the theory that macroscopic thermal expansion of solids is a manifestation of fundamental expansion of the crystal lattice of the material with increase in temperature. Since back reflection of x-ray scattering is sensitive to changes in the lattice constants, this thermal expansion can therefore be correlated to the temperature changes in the material. Specimen used was material from walls of a jet engine. An x-ray camera and high temperature furnace were designed and constructed. Conclusions drawn were that surface temperature measurement of stainless steel is feasible within temperature range of this experiment, and that this method can be extended to measurement of materials where thermocouples or other accepted methods cannot be applied.

5 Measurement of Rapid Temperature Fluctuations in Pulsating Gas Flow, by R. G. Lefeber, Polytechnic Institute of Brooklyn, June 1948, *PIB-7-M*.

The paper offers a detailed exposition of techniques and work carried out in a study of the problem with particular reference to a method utilizing an ultrasonic beam for measuring gas temperatures. Investigations were along these lines: development of experimental supersonic generator to facilitate final design of transducer; investigation of energy transmission in turbulent flow; construction of final transducer; and measurement of temperatures in combustion chambers of pulsejets. Satisfactory transmission could not be obtained, and it is doubtful that sufficiently accurate separation of variables could be made to obtain true temperature recordings.

6 Wedge Thermocouples, by J. H. Hett, New York University, August 1948, *NYU-3-M*.

This paper describes actual construction of a quartz wedge thermocouple. Three surfaces were polished, the knife edge and the two sides. Attempts to evaporate platinum-rhodium alloy on wedges were unsuccessful due to difficulty in oxidation of the metal, and it made a soft coating. Finally, metals in solution were baked on the wedges. Method of coating is described. Mountings were applied by pressure contact. Since the face resistance of these wedges is of the order of 50 ohms, high impedance circuits for high speed recording were necessary. Since an infinitely thin vertex is desirable, theoretically, and since it is not practical in the present type quartz wedge, suggestions for an open type of wedge construction are given.

7 Pyrometer for Measurement of Instantaneous Temperatures of Flames, by J. H. Hett and J. B. Gilstein, New York University, *J. Optical Soc. Amer.*, vol. 39, pp. 909–911, Nov. 1949, *NYU-15-P*.

Dual paths, which are nearly coincident, are used with two photomultipliers and a single filter to obtain on c.r.t.'s records of the radiation from rapidly varying flames. Both temperature and emissivity are determined. Calibration is by a standardized strip lamp. Successful records of the temperature in the combustion chamber of a large pulsejet have been made. The error at 2000 K is of the order of ±20 K.

8 Response of Thermocouples to Rapid Gas-Temperature Changes, by M. W. Carbon, H. J. Kutsch, and G. A. Hawkins, Purdue University, *Trans. ASME*, vol. 72, no. 5, pp. 655–657, July 1950, *PUR-14-P*.

Experimental and theoretical data for response time of thermocouples ranging in wire size from 0.01 to 0.0005 in.; experiments made at temperatures from 70 to 950 F, and air velocities ranging from 0 to 125 fps; equations for computing response time for thermocouples fabricated from fine wires and subjected to sudden air temperature changes.

B Pressure Measurement

1 Application of Statham Pressure Transducers to the Continuous Recording of Instantaneous Pressures, by W. I. Weiss, Polytechnic Institute of Brooklyn, July 1948, *PIB-6-M*.

Describes equipment developed for the application of Statham pressure transducers to the continuous recording of instantaneous pressures. Included are a brief summary and discussion of existing types of dynamic pressure transducers. From harmonic analysis of an actual pressure-time record and several postulated pressure-time relationships, it was concluded that faithful reproduction of the pressure variation could not be accomplished without an instrument capable of recording to at least the eleventh, but preferably the fifteenth, harmonic of the frequency. The instrument herein described was developed for a band pass of 2000 cps, but may be modified satisfactorily up to 5000 cps.

2 Calibration Method and Equipment for Dynamic Pressure Detectors, by P. Torda and W. I. Weiss, Polytechnic Institute of Brooklyn, July 1948, *PIB-8-M*.

Present methods are described and criticized. Requirements for a valid system are presented and a procedure with necessary equipment is described. No actual results are included.

3 Application of Dynamic Strain Gages to the Measurement of Continuous and Average Thrust of Pulse Jet Engines, by P. Torda, W. I. Weiss, E. Shatzki, and J. Lovingham, Polytechnic Institute of Brooklyn, Sept. 1949, *PIB-9-M*.

The method includes (a) the design of a pulsejet engine suspension system, (b) the design of a thrust sensitive linkage, and (c) the results of some test runs. For the actual measurement of thrust, dynamic type strain gages are used as primary detectors. The electrical output of these gages, which is a linear function of the thrust, is amplified and applied to the deflecting plates of a cathode-ray oscilloscope. The signal is recorded by means of a strip camera. The average thrust may be obtained by integrating the amplified primary signal electrically.

4 Frequency Modulation Pressure Recording System, by J. H. Hett and R. W. King, Jr., New York University, *Rev. Sci. Instruments*, vol. 21, no. 2, pp. 150–153, Feb. 1950, *NYU-16-P*.

A simple frequency modulated pressure gage employing a variable capacity element has been devised to measure the oscillating pressures of burning gases. It has been used to measure pressures in pulsejet engines, under conditions where the gas temperatures ranged from approximately 300 to 2450 K and the gage mount vibrated with an amplitude of approximately 0.125 in. The fundamental frequencies of temperature variation, pressure variation, and mechanical vibration were 40 cycles and 220 cps. Under these conditions the pressure response is essentially linear from 0 to 5500 cps.

5 Manometers in Pulsating Systems, by R. J. Kraushaar, New York University, Aug. 1951, *NYU-14-M*.

A series of experiments are described to check the practicality of measuring average pressures in pulsating systems with a connecting tube. Several diameter tubes and typical tube materials were used. It was noted: (a) "average" pressure showed considerable variation with the length of tube; (b) there is a periodic variation related to the frequency of oscillation of the primary system; (c) the tube material affects the magnitude of the peaks; (d) that the tube diameter affects the magnitude of the peaks; (e) that the aperture size will show a gating effect; (f) that the use of a light check valve will permit the reading of maximum or minimum pressure depending upon its directionality regardless of tube length.

6 Final Report on the New York University Pressure Gauge, by R. W. King, Jr., New York University, December 1951, *NYU-11-M*.

Various experiments with the NYU type condenser gage are described. The thermal perturbation of the sensing diaphragm as a function of diaphragm shape, concave or convex, is investigated. Diaphragms lami-

nated with copper thermosetting plastics showed much improvement. A new circuit was devised which uses the connecting cable as a low impedance coupling between a resonant circuit at the gage and a resonant circuit as the receiver. Phase changes in the receiver are measured with 6 BN-6 tubes. The system operates well in gas turbines, but additional cooling is desirable in rockets.

C. Miscellaneous

1 Preliminary Study of a Supersonic Induction Type Wind Tunnel for Cornell Aeronautical Laboratory, by J. L. Moore, O. B. Finamore, and J. G. Wilder, Cornell Aeronautical Laboratory, Sept. 1947, *CAL-9-M*.

A theoretical analysis of the feasibility of employing a high pressure, low volume air source as the primary (inducing) air supply for a supersonic induction type combustion channel is presented. Selecting constant area mixing, and pressure of the primary stream equal to the pressure of the secondary stream at beginning of mixing with the available 420 cu ft of air at 3000 psia feeding an intermediate tank (32.2 psia) through an air reduction valve, the analysis indicates that a test section of 30-in. diameter may be run at a Mach number of 2.0 for 3 min, or a test section of 5-in. diameter for 135 min.

2 Pneumatic Vibrator for Determination of High Temperature Fatigue Properties of Sheet Materials, by F. J. Gillig and L. W. Smith, Cornell Aeronautical Laboratory, Dec. 1947, *CAL-10-M*.

The development of a pneumatic type of testing machine for the evaluation of the fatigue properties of sheet materials at elevated temperatures is described. The manner of operation of the equipment, specimen failure, typical fatigue data, and photographs showing details of the apparatus are included.

3 Application of Image Converter Tube as an Electronic Stroboscope, by G. H. Markstein, Cornell Aeronautical Laboratory; paper presented before the American Physical Society, Washington, D. C., April 1949, *CAL-28-P*.

In the course of work on periodical flow disturbances in flames, it appeared desirable to observe the infrared radiation of the flame gases stroboscopically. It was found that the infrared image converter tube 1P25 could be operated as a stroboscope by applying rectangular voltage pulses to one or several of the electrodes in such a way that the image was blanked except for a short part of the cycle. Apart from allowing stroboscopic observation in the infrared, the device offers advantages over mechanical stroboscopes, owing to the absence of inertia, which enable synchronization even with phenomena which are not strictly periodical; the frequency range of operation appears to be limited only by the time constants of the associated circuits. Applications of the device to combustion studies are discussed.

4 The Application of Schlieren High Speed Moving Picture Techniques to Investigation of High Speed Turbulent Flames, by M. W. Evans, M. D. Scheer, and L. J. Schoen, New York University, May 1948, *NYU-1-M*.

Methods are described for investigating the hydrodynamical properties of high speed turbulent flames by means of high speed moving pictures of a schlieren field. Prints made from frames of typical motion pictures are shown. A discussion of the type of data which may be expected to be obtained from these experiments is included. Application of the data to the understanding of combustion in an eddy-turbulent medium is discussed.

5 The Princeton Pilot Variable Density Supersonic Wind Tunnel, by S. M. Bodgonoff, Princeton University, May 1948, *PR-8-M*.

The design and operation of the pilot variable density supersonic wind tunnel of Princeton University's Aeronautical Engineering Laboratory are discussed in some detail. The tunnel, with a $1 \times 2^1/_2$ in. test section, is designed to operate with stagnation pressures up to 500 psia at Mach numbers from 1.5 to 5.0. It is of the blowdown type, but uses a pressure control system to keep the stagnation pressure constant during a test. Schematic drawings of the equipment and photographs are presented, and a short discussion of the preliminary tests is included. The main result is the observation of a transient at starting due to heat transfer effects. This transient can be almost completely eliminated by precooling the tunnel with a small amount of cold air.

6 An Automatic Recording Extensometer System, by R. J. Flynn and M. Stoll, Polytechnic Institute of Brooklyn, June 1948, *PIB-3-M*.

This paper presents the design of an instrument for the measurement of elongation through the primary, secondary, and tertiary stages of creep phenomena. The system offered provides a means of automatic recording and, being reversible in its operation, allows for the shrinkage accompanying allotropic change in the material under observation. The design incorporates electrical strain gages with a system of beams which are constrained at both ends. As the beam bends, the longitudinal fibers either lengthen or shorten, depending upon their positions with regard to the neutral axis and upon direction of bending.

7 Study of the Use of a Cooled Probe for Sampling Hot Combustion Gas as a Means for Determining Heat Release, by P. E. Erbe, J. T. Grey, and J. L. Beal, Cornell Aeronautical Laboratory, Sept. 1948, *CAL-8-M*. (See *J. Amer. Rocket Soc.*, vol. 23, no. 3, 1953, p. 174.)

Conclusive experimental evidence is presented which shows that a waterjacketed sampling probe using a 0.02-in.-ID tube cools a sample withdrawn from dissociated CO_2 at about 3000 F with sufficient speed to prevent reassociation of the CO and O_2 present in it. Experimental evidence is presented which gives very strong indication that the above sampling probe prevents the reassociation of both CO and O_2 and H_2 and O_2 when sampled from flames at approximately 4200 F.

8 A Mobile High Capacity Blower Unit, by D. Kasner and M. W. Woody, New York University, Nov. 1948, *NYU-5-M*.

A mobile high capacity blower unit consisting of a V-12 aircraft engine with its induction system modified so that the supercharger section can be used on an air compressor is described. Details of the cooling, exhaust, fuel, oil, and electrical systems are also presented.

9 Ionization Flame Detectors, by H. F. Calcote, Princeton University, *Rev. Sci. Instruments*, vol. 20, no. 5, pp. 349–352, May 1949, *PR-35-P*.

Two new ionization methods of detecting flames are described for use in the measurement of flame speeds. In one, the loading characteristics of a high-frequency oscillator are utilized by causing the flame to pass through an oscillator tank coil. The second method employs the flame conductivity by placing two ring electrodes around the exterior of a combustion tube, and applying a d-c voltage across them through a large series resistance. The voltage pulse created by either method when the flame passes the detector is used to trigger an electronic chronoscope. Both methods have the distinct advantage over previous methods of flame detection in that the direct measurement of flame speeds can be made without the introduction of electrodes or wires into the combustion tube. The oscillator detector has the additional advantage that the point at which the measurement is made can be varied at will.

10 Note on the Use of the Shock Tube as an Intermittent Supersonic Wind Tunnel, by G. Rudinger, Cornell Aeronautical Laboratory, *Phys. Rev.*, vol. 75, no. 12, pp. 1948–1949, June 1949, *CAL-49-P*.

The use of the shock tube as an intermittent supersonic wind tunnel is discussed in a letter to the editor. The existence of two distinct Mach numbers on either side of the interface during a shock tube experiment is pointed out. It is shown that the use of the flow behind the interface not only eliminates the upper Mach number limitation but also may lead to a useful testing time which is considerably longer than that corresponding to the flow ahead of the interface.

11 Development of High Temperature Metalloscope, by E. H. Kinelski, Cornell Aeronautical Laboratory, Sept. 1949, *CAL-31-M*.

A literature search ascertained the practicability of using a high temperature metalloscope as a tool in the study of the microstructures of metals at high temperatures. Following the development of the equipment assembled to form a high temperature metalloscope, the photo-and-cine-micrography is discussed for 24S T aluminum. The ternary eutectic melting was photographed at approximately 950 F. The high temperature metallographic study of SAE 4130 steel and 70–30 cartridge brass was unsuccessful due to oxide formation.

12 A Diffraction Grating Interferometer, by R. Kraushaar, New York University, *J. Optical Soc. Amer.*, vol. 40, no. 7, pp. 480–481, July 1950, *NYU-24-P*.

A compact new kind of interferometer is described which can produce much larger fields of view than the conventional Mach-Zehnder interferometer. The instrument is an outgrowth of the Ronchi-schlieren apparatus, and involves only reflections of light beams in the essential portions of the apparatus.

13 Influence of Resolving Power on Measurement of Correlations and Spectra of Random Fields, by M. S. Uberoi and L. S. G. Kovasznay, Johns Hopkins University, Jan. 1951, *JHU-1-R*.

Functional relations are derived between the true correlations and spectra of a random field and those measured with a probe of finite resolving power. The case of a probe having zero resolving power in one direction (e.g., infinitely long hot wire) is examined; and it is shown that, in the case of homogeneous random fields, the true correlations and spectra can be recovered from the corresponding measured quantities. These relations are applied to turbulence measurements by hot wire anemometers and optical methods. Explicit calculations of hot wire length effect are made for some simple velocity and temperature spectra.

14 Dynamic Method for Measuring the Specific Heat of Metals, by A. M. Nathan, New York University, *J. Appl. Phys.*, vol. 22, pp. 234–235, Feb. 1951, *NYU-6-M-P*.

Used for a preliminary study of the specific heat curves of low C steel at the phase transformation points. The cylindrical specimen, 20 cm long and 3 mm diam, is heated electrically by Pb accumulators, and a rapid rise in temperature (1000°/sec) is produced. The voltage drop across the specimen, the heating current, and the temperature, measured by a Pt/Pt/13 per cent Rh thermocouple, are recorded electronically. A block diagram of the setup is given. Indications of the curie point at 769 C were obtained.

15 High Speed Stereoscopic Schlieren System, by J. H. Hett, New York University. *J. Soc. Motion Picture and Television Engineers*, vol. 56, pp. 214–218, Feb. 1951, *NYU-8-P*.

A stereoscope schlieren system is described. A 16-mm Fastax camera is used to photograph 10-in. sections of a 4- by 4-in. flame tube at 9000 frames/sec. A polarizing projection system is used. The depth effect is observed with burning gases provided sufficient detail is available in the image.

16 Thermistor as a Flowmeter, by R. W. King, Jr., New York University, Oct. 1951, *NYU-10-M.*

Early circuit designs measured only fluctuations in flow rate. Later developments employ a feedback bridge circuit using a d-c amplifier to maintain the thermistor at a constant temperature. The calibration becomes independent of the gain, being largely determined by the constant in the feedback bridge. Ambient temperature effects in the liquid have been reduced by using a second thermistor in a bridge circuit which measures only the temperature. Experiments were confined to low flow rates (2 gal/hr).

17 The Design, Construction, and Operation of the Princeton 4 by 8 Inch Variable-Density Supersonic Tunnel, by S. M. Bogdonoff, Princeton University, Oct. 1951, *PR-44-R.*

The design, construction, and operation of the Princeton 4- by 8-in. Variable Density Supersonic Tunnel are described in some detail. The tunnel has been designed for a range of Mach numbers from 1.5 to 5.0 and has operated in a Reynolds number range from less than 1×10^6 up to 60×10^6. Model mounting and tunnel starting problems are discussed and the present research program now under way is outlined.

18 Experimental Investigation of Optical Methods for Measuring Turbulence, by L. S. G. Kovasznay and P. C. Clarken, Johns Hopkins University, Jan. 1952, *JHU-3-R.*

Optical methods are explored for measuring statistical properties of turbulent density fluctuations. Analysis of shadow pictures of turbulent regions in wake of special "grid projectiles" can yield microscale of turbulent density fluctuations of right order of magnitude. Experimental comparison between hot wire anemometer and optical methods performed in flow field where both types of measurements were feasible. Experiments proved optical methods are practicable in certain domain of variables but not superior to hot wire anemometer where latter is applicable.

19 The Relation Between Sampling Tube Measurements and Concentration Fluctuations in a Turbulent Gas Jet, by J. M. Richardson, H. C. Howard, Jr., and R. W. Smith, Jr., U. S. Bureau of Mines, Fourth Symposium (International) on Combustion, Williams and Wilkins, Baltimore, pp. 814–817, 1953, *BUM-3-P.*

An extension and modification of the analysis of Hawthorne, Weddell, and Hottel (Third Symposium on Combustion, Flame, and Explosion Phenomena, Williams and Wilkins, Baltimore, 1949, pp. 266–288) are made. The first modification is the redefinition of the distribution of the concentration, and the second modification is the choice of a more realistic type of function than the Gaussian for describing the distribution of concentration in the gas jet.

Index by Author

ADAMSON, T. C., JR.—II-C-33
AGNEW, W. G.—II-C-18
ALBERT, R. J.—VI-A-12
BADIN, E. J.—III-A-1, 2, 3, 4, 5, 6, 7, 11, 13, 14; IV-B-a-3
BEAL, J. L.—II-A-10; IV-E-3; VI-C-7
BEIGHLEY, C. M.—II-C-21; V-C-4
BENDER, A.—VI-A-4
BERNATH, L.—IV-D-4
BETCHOV, R.—II-C-36
BLAIR, P. M.—II-B-5
BOGDONOFF, S. M.—VI-C-5, 17
BOWDITCH, F. W.—II-C-18; IV-B-b-5
BRICK, J. H.—V-A-1
BRINKLEY, S. R.—IV-B-6
BROKAW, R. S.—III-A-6, 8, 14, 16, 17, 21; B-1; IV-B-a-5, 6
BROWNING, J. A.—IV-C-9, 10, 16; E-4, 5, 11
BURWASSER, H.—IV-B-a-12
BUTTNER, H. J.—II-C-18; IV-B-b-5; C-1, 5
CALCOTE, H. F.—IV-A-4; C-19, 21; IV-E-2; VI-C-9
CARBON, M. W.—IV-A-1, 2; VI-A-8
CHANG, C. T.—II-C-39, 40
CHARVONIA, D. A.—IV-A-3
CHARYK, J. V.—II-B-1, 2
CHIN, C.—II-A-2
CHOUDHURY, A. P. R.—II-B-4
CHOW, T.—II-C-35
CLARKE, R. P.—II-A-14; III-A-9, 15
CLARKEN, P. C.—VI-C-18
CLINGMAN, W. H.—IV-B-a-7, 15, 16
COHEN, E. S.—IV-D-7
COOK, E. B.—IV-B-a-11; E-12
CRAMER, R. H.—II-C-23
CULLEN, R. E.—II-C-41
CULVERWELL, J. F.—II-B-6
DASHIFSKY, W.—II-C-7
DENNISTON, D. W., JR.—IV-B-b-9
DIEDRICK, I. G.—V-B-6
DORSEY, C. L., JR.—III-B-4
EINBINDER, E.—IV-C-2
ELIAS, P.—V-B-8
ERBE, P. E.—IV-E-3; VI-C-7
EVANS, M. W.—IV-B-a-6; b-3, 4; VI-C-4
FANKUCHEN, I.—VI-A-4
FERRARI, C.—II-C-23
FINAMORE, O. B.—II-C-10, 11; V-B-5; VI-C-1
FINKELSTEIN, A. B.—II-A-18
FLOYD, W. W.—IV-B-b-5; C-1
FLYNN, R. J.—IV-C-6
FOA, J. V.—II-C-16; V-A-5
GARVIN, D.—III-A-29, 31
GILLIG, F. J.—I-C-9-, 13; VI-C-2
GILSTEIN, J. B.—VI-A-7
GLASSMAN, I.—II-B-7
GLICK, H. S.—III-A-27
GOING, L. H.—III-B-4
GOODMAN, T. R.—II-C-19
GREY, J. T.—IV-D-1, 2; E-3; VI-C-7
GRIFFITH, W. C.—II-C-26
GROUNDS, P. W.—II-B-6
GROVER, J. H.—IV-B-b-7; E-8
GRUMER, J.—IV-B-a-11; E-12
GUARNIERI, G. J.—I-C-1, 2, 7, 8, 13, 14
GUNN, S. V.—IV-A-1
HARRINGTON, R. P.—II-A-7
HASS, H. B.—III-B-5
HAWKINS, G. A.—VI-A-1, 2, 8
HENDERSON, J. B.—II-A-12
HENRY, O. H.—I-C-4, 6
HERTZBERG, A.—III-A-27
HETT, J. H.—VI-A-3, 6, 7; B-4; C-15; V-B-14
HOLCOMB, D. E.—III-A-10; B-4, 5
HOTTEL, H. C.—IV-E-7, 10
HOWARD, H. C., JR.—VI-C-19
HUDSON, G. E.—II-C-14
HUNT, H.—III-B-2
HUNTER, P. C.—III-A-7, 11
JOHN, R. R.—II-B-2
JOHNSON, E. F., JR.—I-B-1
KAHANE, A.—II-C-6, 9, 26; V-B-6, 16
KAMRASS, M.—II-C-3, 4
KARLOVITZ, B.—IV-B-b-6, 8, 9; E-8
KASNER, D.—VI-C-8
KAUFMAN, L.—II-A-7
KEYES, F. G.—I-A-1, 2, 3, 4
KIBLER, G. M.—III-B-2
KINELSKI, E. H.—VI-C-11
KING, I. R.—IV-A-4; C-19, 21
KING, R. W., JR.—VI-B-4, 6; C-16
KISPERSKY, J. P.—III-B-5
KLEIN, G.—IV-B-a-13, 14, 17
KLEIN, R.—III-A-26
KNAPSCHAEFER, D. H.—IV-B-b-9
KNUTH, E.—II-C-21
KORTRIGHT, J. M.—I-C-15
KOVASZNAY, L. S. G.—II-C-24, 27, 32; IV-C-13; VI-C-18
KRALL, W. G.—IV-E-9, 11
KRAUSHAAR, R. J.—VI-B-5; C-12
KUTSCH, H. J.—VI-A-8
LAMB, G. G.—II-B-6
LANGENHEIM, R. H.—I-C-15
LEES, L.—II-C-5, 6, 9, 13
LEFEBER, R. G.—VI-A-5
LEMELSON, J.—V-B-12
LEVY, A.—II-A-15, 17
LEWIS, B.—IV-B-a-8; E-8
LIBBY, P. A.—II-A-7, 8, 13, 14
LOGAN, J.—II-C-1, 2, 7, 10, 11, 20; V-B-3, 4, 5, 9, 15
LOVINGHAM, J.—IV-B-3
MACDONALD, J. K. L.—IV-B-b-1, 2
MANTON, J.—III-B-6; IV-B-a-8, 10
MARINO, A. A.—II-C-26
MARKSTEIN, G. H.—IV-B-a-4; C-3, 4, 6, 7, 8, 12, 14, 15, 17, 18, 20; E-1; VI-C-3
MELESE, G. B.—II-C-22, 28
MENKES, H. R.—II-A-14
MESSINGER, C. W., JR.—V-B-16
MILLER, E. L.—IV-B-b-4
MILLER, J.—I-C-1, 2, 7, 8
MILLER, K. D.—II-C-12
MILLIKEN, B. B.—IV-B-a-10
MOORE, J. L.—VI-C-1
MORDUCHOW, M.—II-A-9
MORRISON, R. B.—II-C-33, 41
MURPHY, G. M.—IV-D-3, 6
NATHAN, A. M.—I-C-11; VI-C-14
NELSON, J. M.—III-A-10
NESS, N.—II-A-5, 11
NEURINGER, J. L.—IV-B-b-2
NICHOLLS, J. A.—II-C-41
NIKURADSE, I.—II-C-18
OGURA, Y.—II-C-37
ONG, S. B.—II-C-38
PALLONE, A.—II-A-13
PARSHALL, N. E.—IV-C-1
PEASE, R. N.—III-A-1, 6, 7, 11, 14, 15, 16, 19, 21, 24, 25, 28, 30, 32; IV-B-a-1, 2, 3, 5, 7, 12, 15, 16; IV-E-2
PERSON, R. A.—IV-E-7
POLANYI, M. L.—IV-E-1
POOL, H. L.—II-B-1
PORTER, P. K.—I-C-10
POWELL, H. N.—IV-D-4
PROBSTEIN, R. F.—II-C-14
RAMEY, H. J.—II-A-12
REISSNER, H. J.—V-B-7
RICHARDSON, J. M.—IV-E-5; VI-C-19
RINALDI, L. D.—II-C-8, 15
ROBISON, A. G.—IV-D-4
ROTHGERY, G. H.—IV-D-1, 2, 5
RUDINGER, G.—II-C-2, 7, 8, 10, 11, 15, 16, 29, 31, 34; IV-C-3; V-B-1, 11, 13; VI-C-10
SALVAGGI, J.—I-C-14
SCESA, S.—II-A-15
SCHEER, M. D.—III-A-20; IV-B-b-3, 4; VI-C-4
SCHIPPEREIT, G. H.—I-C-3, 5, 6
SCHOEN, L. J.—IV-B-b-3, 4; D-3, 6; VI-C-4
SCHUBERT, C. C.—III-A-28, 29, 30, 31, 32
SCHWARTZ, D.—IV-C-18, 20
SCHWARTZ, L.—II-C-22
SCURLOCK, A. C.—IV-B-b-7; E-8
SEBAN, R. R.—II-A-15, 17
SELLER, J. P.—V-A-4
SHAFER, H. J.—V-B-16
SHATSKI, E.—VI-B-3
SHEFFY, W. J.—I-B-1
SHIPMAN, C. W.—IV-C-13
SHORE, L.—IV-B-b-10, 11
SIMPSON, H. C.—IV-E-10
SINGER, J. M.—IV-B-a-9, 11; E-12
SMITH, J. M.—II-A-12
SMITH, L. W.—VI-C-2
SMITH, R. W., JR.—III-B-6; VI-C-19
SOMERS, L. M.—II-C-34; IV-C-12, 14
SQUIRE, W.—II-C-19; III-A-27; IV-C-18
STERBUTZEL, G. A.—II-A-10
STEPHENS, E. R.—III-A-12, 19

(Continued on page 688)

Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*
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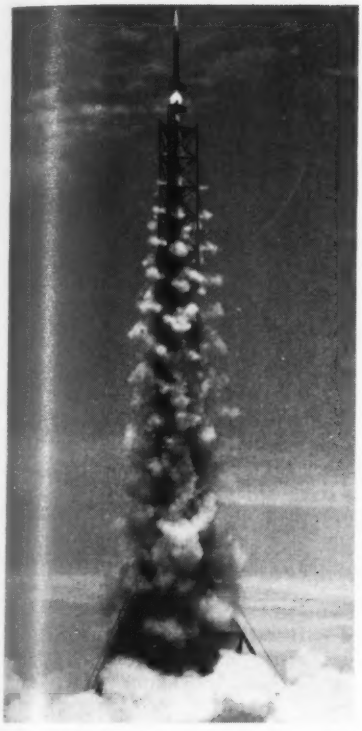

AEROBEE-HI sets new altitude record

Success on Six

FIVE tries and 10 months after its initial attempt, the Aerobee-Hi finally established an altitude record for an American-built, boosted rocket as it rose 163 miles over White Sands, N. Mex., June 29.

Produced by Aerojet-General under Naval Research Laboratory contract, the high altitude research vehicle had been plagued by trouble at its first five firings. Here, in brief, is what happened:

- Aug. 1955. Complete failure due to regulator trouble. In this instance, it was a case of misdesign. The high pressure gas regulator used for this firing was originally designed for Nike vehicles. The safety feature built into the regulator to make the Nike safe in firing, actually made the Aerobee-Hi too safe; i.e., it wouldn't fire at all. The regulator was modified and proved successful.
- Dec. 1955. Complete failure due to "hard start"; i.e., engines blew up when engineers tried to fire the rocket.
- May 1956. Complete failure due to fault in range safety circuitry.
- May 1956. This firing was not a complete failure. Rocket rose 117 miles before thrust chamber failed.
- June 1956. Thrust chamber again failed. This time, the rocket climbed only 40 miles. The thrust chamber trouble was finally located and corrected.

Technically a two-stage rocket, the Aerobee-Hi outreached the 158-mile record set in May 1954 by the single-stage Viking, but fell short of the 250-mile altitude attained by the two-stage German V-2 carrying a WAC Corporal in Feb. 1949.

Speed of the Aerobee-Hi during its record run was pegged at 4435 mph. Moreover, reports from White Sands indicate the rocket performed with exceptional stability, did not tumble after burnout. This reported stability, said Aerojet's Chandler Ross, points to the possibility of pushing the Aerobee-Hi to even greater heights without having to redesign the vehicle itself.

Now in the process of designing and building the second-stage rocket engine for Project Vanguard, Aerojet indicates that this new engine will incorporate many features of the Aerobee-Hi. Meanwhile, the company is continuing production of its current Aerobee models, plans to produce 68 Aerobees and Aerobee-Hi's for use by the Air Force, Navy, Army Signal Corps and other scientific agencies during the International Geophysical Year 1957–1958.

Most of the new Aerobee-Hi's will resemble their record-setting predecessor, which measures up as follows: over-all length, including booster, 372 in.; diameter, 15 in.; weight, empty, 269 lb; propellant load, 1080 lb; instrument pay-load, 130 lb; total weight, about 1500 lb. The June 29 model was equipped with a conventional Aerojet-Aerobee liquid motor; certain modifications used in two previous experimental firings were discarded.

A new ceramic thrust chamber, now under development at Aerojet, may be used in future Aerobee-Hi's, says the company, provided it proves out in tests to be held later this year.

USAF Spreads LPR Engine Supply

WITH one high-level decision last month, U.S.A.F. assured itself of at least two supply sources of large, liquid propellant rocket engines, boosted over-all supply, and provided a bromide for the two suppliers, Aerojet-General Corp. and North American Aviation, Inc.

The decision: to assign operation of the Air Force lpr production facility, now under construction at Neosho (Mo.), to North American instead of Aerojet-General as originally planned. Slated for completion in 1957, the brick-and-mortar unit will be operated by NAA's Rocketdyne division as a branch of its Canoga Park (Calif.) rocket plant. Actual ownership of the Neosho facility will be retained by the Air Force.

Background: Contracted to Aerojet about two years ago, operation of the facility would have forced a geographical split upon the company which already has a liquid rocket plant in Sacramento (Calif.) with plenty of room for expansion. Rocketdyne, on the other hand, wanting to enlarge its liquid rocket operations, was faced with restricted expansion opportunities in Canoga Park. Thus the reassignment solved both firms' growth problems.

Moreover, says North American, the transition itself will be smooth, create no new problems. Construction will continue, as originally scheduled, under Air Force contracts; and such things as job application forms—already filled in by prospective Neosho employees for Aerojet—will be taken over by Rocketdyne.

Aerojet, meanwhile, is going ahead with expansion of its large, liquid propellant rocket engine production at Sacramento, will add among other things a $13-million manufacturing unit which will boost the firm's total production area 360,000 sq ft.

In Reserve: Sitting on the sidelines, of course, is Reaction Motors, Inc. (Denville, N. J.), a possible third source of supply for the large, liquid rocket engines. Under an R&D contract to the Air Force, RMI presently is not geared for quantity production of large, liquid propellant rocket engines. But, says RMI, it would only be a matter of a few weeks at most before it could get rolling.

Curtiss-Wright Corp. (Wood-Ridge, N. J.), producer of the Bell X-2 rocket engine, is not now active in any program dealing with large lpr power plants. Its primary interest is in low- and medium-thrust engines; however, as the company points out, this does not gainsay its consideration as "a potential supplier for the large, lpr engines."

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In somewhat the same position, Bell Aircraft Corp. (Buffalo) has no contracts in hand for work on the large, lpr engines, but considers itself a prime potential source because of experience gained in closely allied fields. Bell summarized the feelings of most other engine makers when it declared itself "ready, willing, and able to produce large, liquid propellant rocket engines" though not now doing so.

Significant, perhaps, is the fact that General Electric Co. (Evandale, O.), the only other major lpr engine producer, does not consider itself a potential source of the large power plants. Supplier of lpr engines for the Hermes project and for the first stage of the currently abuilding Vanguard vehicle, GE declares that it is not now building anything in the large thrust class, nor can it see itself doing so in the future.

MISSILES

● Antimissile missiles are on the way. In secret testimony released last month by the Senate subcommittee investigating U. S.-Russian air power, Lt. Col. Woodrow B. Sigley, chief of the air defense branch of the Army's missile division, said that the Army is confident it will have a counterweapon ready in time to meet any threat of long range missiles in 1960 or 1961. It is assumed that he had Nike II in mind.

● Italy's Defense Minister, Paolo Emilio Taviani, recently disclosed that his country will soon be equipped with guided missiles. Type and source of the new arms were not revealed, but the move is part of a Western effort to bolster defenses in the vital Mediterranean area.

● Range of the Navy-developed Talos, according to Navy Secretary Thomas, far exceeds that of the Terrier, the surface-to-air missile now in operation with the fleet. Without going into details, he said that the Talos had recently passed "an important milestone" in development.

● Curtiss-Wright recently took the wraps off its supersonic ramjet engine. Work on the engine began in 1947; first controlled flight was made in 1952.

● A new Soviet ramjet missile with a speed of Mach 3 and a range of 180 miles has been reported. The missile is said to have a diameter of 11 in. and to be capable of carrying a nuclear warhead.

● Boeing and Marquardt confirmed use of Marquardt ramjet powerplant for the BOMARC IM-99 missile. The IM-99 will be built in Wichita.

● Marquardt has started development on a 36-in.-diam supersonic ramjet for USAF. Currently in production is a ramjet which tips the scale at 500 lb and has a 10,000-lb thrust at Mach 2.5–3.

● An air-to-air missile, the Falcon (now called GAR-1), will be installed on the new McDonnell F-101 jet interceptor.

● Petrel, air-to-surface missile recently revealed by the Navy, is built by Fairchild, designed for use against enemy ships. Equipped with electronic guidance, Petrel is powered by a J44 torbojet engine. Range of the missile is large enough to keep the mother aircraft out of the range of the target's air defense.

AIRCRAFT

● Competition for new line of U.S.A.F. aircraft is currently under way. Among the sought-after aircraft are WS-110A, the "chemical fuel" bomber designed for 10,000-mile range, altitudes of 70,000 ft, and a speed of Mach 2 (Boeing and North American); WS-300A fighter-bomber (North American and Republic); WS-202A long-range interceptor (Northrop and North American); and WS-302A tactical bomber (Douglas and Martin).

● F3H-2M is the new missile-carrying version of the McDonnell Demon carrier-based jet fighter. The plane carries a number of Sparrow missiles under its wings.

● Newest and speediest fighter is the Lockheed F-104A Starfighter. Power comes from a GE J-79 turbojet engine. Other features: short, razor-thin, down-droop wings; gross weight, 14,000 lb; span, 9 ft 11 in.; length, 54 ft 9 in.; height, 13 ft 6 in. Speed with a J-65 prototype was reported at 1192 mph. Speed with the J-79 is said to be over Mach 2.

● The swept-wing Skylark 600 is Convair's new medium-range jet transport. Power comes from four GE CJ-805 turbojets (commercial version of the J-79). Deliveries are slated for early 1960. Specifications: span, 118 ft 4 in.; length, 118 ft 5 in.; tail height, 35 ft 2 in. First-class version will carry 80 passengers. Maximum gross takeoff weight is 170,000 lb. Cost is about $3.3 million each.

● The F4H-1 is the Navy's new all-weather supersonic attack-fighter. McDonnell will build the plane on a $38 million contract. The company will also build additional F3H-2N Demon fighters for the Navy, some of which will carry new missiles.

● Future supersonic high altitude jet aircraft may utilize Douglas' new capsule-type escape system. The Navy and Douglas say the capsule will

be interchangeable in many types of aircraft and adaptable to manned space craft.

● The B-66 tactical bomber is now in operational status. The Douglas twin-jet, declares U.S.A.F., is able to carry an H-bomb.

● First Wichita-built B-52 recently made its maiden flight. The Boeing Stratofort is powered by eight P&W J-57 turbojets of 10,000-lb thrust each. Range is over 6000 miles and ceiling is over 50,000 ft. The 200-ton craft has a span of 185 ft, a length of 156 ft, and a tail height of 48 ft.

● Tupolev 104, new Soviet jet airliner flown into London on a recent visit by high Red officials, is said to have a range of 2000 miles, a cruising speed of 500 mph at 33,000 ft. The craft can carry 52 passengers and is powered by two turbojet engines of about 20,000-lb thrust each (sea level static). Fuselage is about 120 ft long; span, 118 ft; sweepback, 30 degrees; and total height, 33 ft. Indications are that the craft drew on Soviet Badger and Bison jet-bomber developments. The Tu-104 will be used on the Moscow-Peking route and between Moscow and European cities.

● Vautour, the French light interceptor-bomber, is going into production. The SNCASO plane is powered by two Avon 41 turbojets of 9925-lb thrust each.

COMPANIES

● Hicks Corp. (Boston, Mass.) was recently cited by Navy for its part in Terrier program. The only supplier of Terrier rocket motors classed as small business, Hicks has furnished over 50% of units delivered to date.

● Republic Aviation Corp. (Farmingdale, N. Y.) has received $15 million in new Air Force contracts for modernization of early model operational jet aircraft.

● To cover a new financing program, Marquardt Aircraft Co. (Van Nuys, Calif.) recently filed a registration statement with SEC, expects to offer new shares shortly. Part of the projected proceeds will probably go toward the planned $6-million expansion of the firm's ramjet test center at Van Nuys.

● Aerojet-General Corp (Azusa, Calif.) has named the Garrett Corp.'s Ai-Research Aviation Service division as distributor for its aircraft auxiliary rocket engines (15KS-1000-A1). Recently released by the Navy for civilian use, the engine is a smokeless, solid propellant rocket unit.

● Callery Chemical Co. (Callery, Pa.), subsidiary of Mine Safety Appliances Co., will build a $38-million, high

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MARTIN

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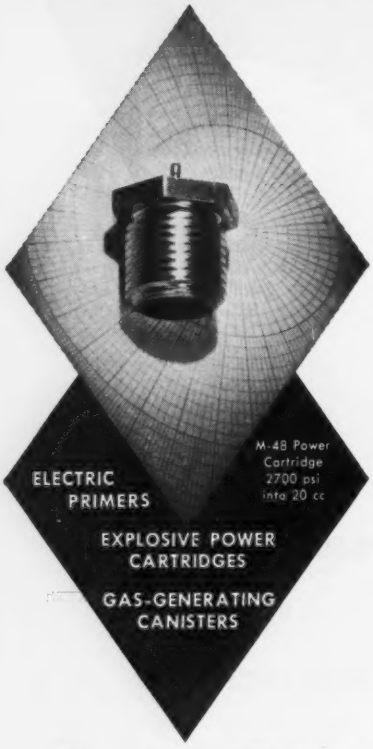

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energy fuel plant under Navy contract. The plant will be located on government owned land near Muskogee, Okla.

● On June 29, International Business Machines Corp. (New York) shipped the first SAGE (Semi-Automatic Ground Environment) computer system from its Kingston (N. Y.) plant to McGuire Air Force Base in New Jersey. Designated AN/FSQ-7, these giant computers will help tie together the new continental air defense complex of radar, ships, planes, communications, missiles, and people.

● Independence is apparently the corporate byword of Systems Laboratories Corp. (Los Angeles), a newly formed organization specializing in interplanetary travel. Headed by John L. Barnes, the firm is composed largely of former Lockheed scientists and engineers who like Dr. Barnes left the aircraft company last December because of disagreement with management policy. At that time, the group formed Systems Research Corp. to continue the work they had been doing. Then, last May, Ford Motor Co. took over SRC, used it as the nucleus of its new missile systems subsidiary, Aeronutronic Systems, Inc. So, to preserve their hard won autonomy, Dr. Barnes and many of his associates formed Systems Laboratories Corp.

● Convair will locate its new Atlas plant on a 275-acre site near Sorrento Canyon, Calif. Scheduled for completion next year, the 1-million sq ft unit will cost an estimated $40 million.

● Thiokol Chemical Corp. will build a $2-million rocket and guided missile center in Corrine, Utah.

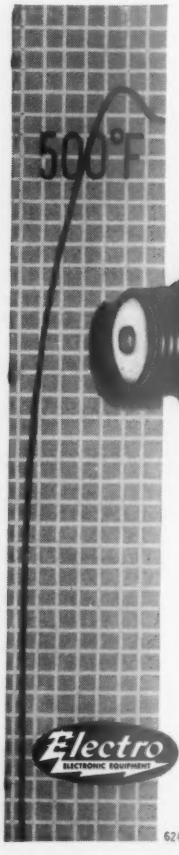
● DuMont's new Missile Engineering Dept. plant will be headquartered in Los Angeles, do research and manufacturing of missile electronic equipment.

● American Machine and Foundry Co. will build missile handling and launching systems at Rochester (N. Y.) under an $11-million government contract.

● Republic Aviation Corp.'s (Hicksville, N. Y.) plans to double research, development, and production facilities of its Guided Missile Div.

● Martin's new Titan plant will be on a 4000-acre site, 15 miles south of Denver. Slated to go into operation next year, the ½-million sq ft plant will employ over 5000 persons.

● Missiles and unmanned aircraft will receive advanced studies by Lockheed on a 22-acre site at Stanford University, Palo Alto, California. In



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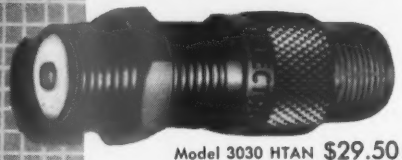

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addition, a new branch of the Missile Systems Division will be established at a new base at Sunnyvale, Calif. About $7 million will be spent on the two projects.

● Missile engineering is now a separate entity at Douglas Aircraft. The newly established department is located in the Santa Monica missile production building. Eight active missile projects are under way with the Air Force, Army, and Navy.

● Santa Barbara, Calif., will be the future location of the new Aerophysics Development Corporation facility. The subsidiary of Studebaker-Packard Corp. will construct a $1.3 million missile facility. Two missile projects are under way—development of the Dart missile for the Army and a rocket test vehicle for the Air Force.

RESEARCH

● In a recent ARDC rocket experiment, an Aerobee ejected 18 lb of nitric oxide into the "atmosphere" at night some 60 miles above the earth. At this altitude there is considerable atomic oxygen which is formed by the action of ultraviolet radiation on molecular oxygen. The purpose of releasing nitric oxide was to catalyze the reformation of molecular oxygen from the atomic state. This combination was accompanied by an energy release—evidenced, in the experiment, by a spot of light about twice the intensity of Venus. In ten minutes, this "star" spread to a width of about three miles.

In a day test, solar radiation produced a giant cloud of charged particles. Scientists of the Air Force Cambridge Research Center succeeded in reflecting radio signals from the cloud.

● Armour Research Foundation is using its "strong" shock tube to study the penetration of metals by high velocity particles in order to determine damage that might be done to a satellite vehicle by impact of airborne dust and by heat generated by friction. Speeds of 4000 fps have been generated. Common dust shot at this speed penetrated an eight-mil thick copper plate.

● Do you have an idea for a new missile? Or a new principle which might revolutionize aircraft design? Or a material which can stand temperatures that turn ordinary metals to liquid? If so, the Air Force has set up a system to evaluate them. Correspondence should be addressed to Assistant for Innovations, RDTE, Headquarters, Air Research & Development Command, Box 1395, Baltimore 3, Md.

● According to NACA engineers, the

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Features of the Model 158-5490 system include 0.1v/cm to 100v/cm sensitivity; over-all linearity of 0.25 mm over the entire 4 cm of the chart; drift less than 0.5 mm/hour; push-pull or single-ended input; miniaturized dual-channel DC amplifiers of improved current feedback design; 5 meg. input impedance each input lead to ground; true rectangular coordinate recording; nine chart speeds from 0.25 to 100 mm/sec. Frequency response is flat to 20 cps, down 3 db at 60 cps for all amplitudes to 4 cm peak to peak.

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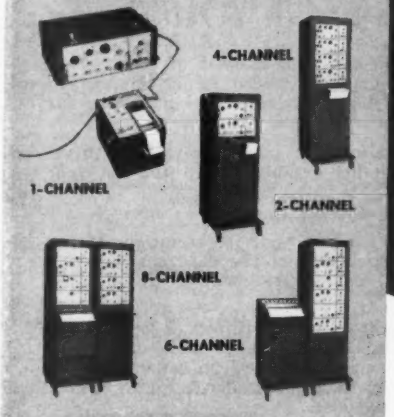

In laboratories, production testing facilities and field installations nationwide Sanborn 150 Series Oscillographic Recording Systems are proving their versatility and value. Users have a choice of basic systems ranging from 1 to 8 channels . . . "packaged" as portable units or in vertical mobile cabinets . . . and twelve interchangeable plug-in preamplifiers permitting rapid, economical changeover to new input requirements.

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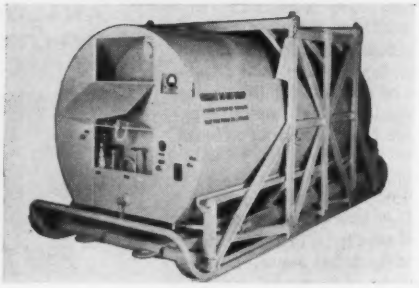

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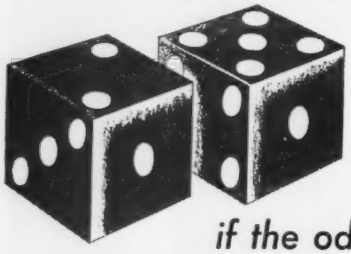

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following are needed for high combustion efficiencies in high speed ramjet systems: fuel mixtures in a narrow composition range near stoichiometric; enough time and temperature to bring the new charge to ignition or flame conditions; and enough time and volume for complete burning under turbulent conditions.

● Design and construction of a new solar furnace is under way by the U.S.A.F. at a 9000-ft-high mountain site near Holloman AFB (N. Mex.). Under ideal conditions, a temperature of 7000–8000 F may be obtained for determining thermal effects of nuclear weapons and for high temperature chemical research.

MATERIALS

● Ceramic coatings show promise of protecting metal tailpipes. In full-scale ramjet tests at Marquardt, Norton Co.'s Rokide A (alumina) coating reduced metal temperatures 360 F at a temperature of about 2200 F. The 30-mil coat had good mechanical bonding properties. Zirconia refractory coatings are also under test. Use of such coatings is expected to help out during transient thermal severities.

● Certain plastic laminates have definite high temperature, short-life characteristics useful in missile work, says Thompson Fiberglass Co. (Los Angeles). Items: rocket guide vanes with a life of two minutes at over 4500 F; nose cones, good at temperatures over 750 F for 30 minutes; fin units on booster rockets which hold up for one minute at 2400 F. When temperatures exceed the melting point of metals, burn-through gives laminates longer service life than metals.

● Lubricants which can operate between 1000–2000 F are on the way, predicts General Electric.

● Stainless steel will account for 50% or more of the weight of future supersonic planes, declares Republic Steel.

FACILITIES

● A glimpse into North American's Propulsion Field Lab at Santa Susana revealed a facility comprising an area of 3 square miles, manned by a staff of 1833. High thrust rocket engines for Atlas, Redstone, and Navaho missiles are tested here in seven sets of static test stands. Most stands are of the vertical type and capable of handling about $^1/_2$- to 1-million-lb thrust.

● Mach 5 is the capability of a new $3.5 million wind tunnel for Chance Vought Aircraft, Dallas, Texas. Of blow-down design, the tunnel is about 265 ft long. Air to operate the tunnel

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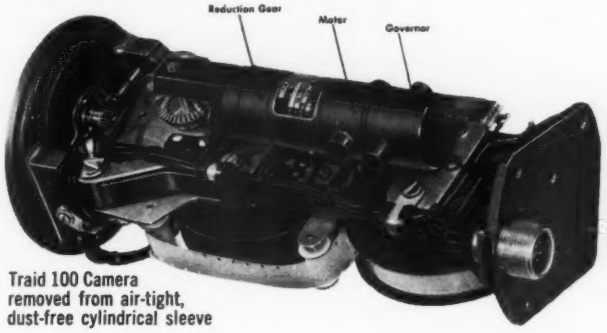
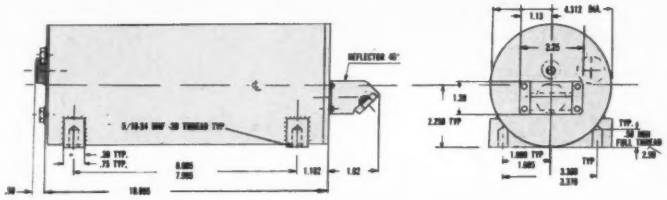
The ejectable feature of the Traid 100 is coupled with parachute suspension. Its unusual ruggedness, its ability to float, the ease of mounting and its reliability of operation make this camera especially useful in both military and civilian testing.



Traid 100 Camera
removed from air-tight,
dust-free cylindrical sleeve



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will be stored in 6 steel tanks at 600 psi and will pass through a 4-ft sq test section where plane or missile models up to 4 ft long can be tested. Completion date is 1958.

● The Air Force Missile Test Center (Fla.) now has in operation a $\$^1/_4$-million digital data transmission system for the 1000-mile-long submarine cable. Electronic Engineering Co. (Los Angeles), builders of the data system, will also supply a complete high speed camera and remote control system for the rocket test track at Edwards AFB (Calif.).

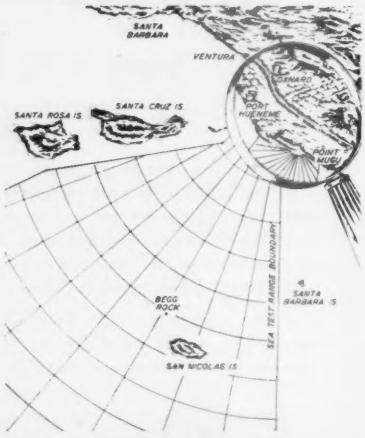
● A look at its Malta Ramjet Propulsion Laboratory was provided by General Electric. The lab, built during 1949 and 1950 at the Malta Test Station (Ballston Spa, N. Y.), is designed to test connected pipe ramjets and combustors. Ramjet engines of 24-in. diam have been tested along with combustors up to 18 in. In addition to the full-scale facility, a 6-in. rig and a 2 × 2 visual combustor rig have been operated. Ten Allison V-1710-111 liquid-cooled aircraft engines drive superchargers as air compressors. Specialized equipment includes an infrared gas analyzer, a sodium D line reversal apparatus for temperature measurements, and an air supply system furnishing 45 lb of air/sec at three atmospheres or 90 lb/sec at two atmospheres.

Project SQUID

(*Continued from page 680*)

STEVENS, W. F.—II-B-4, 6
STOLE, M.—I-C-5; VI-C-6
STORM, M. L.—II-A-6
STUART, J. G.—IV-B-a-3
SULLIVAN, M. V.—III-B-2
SUMMERFIELD, M.—V-C-1, 3
TANFORD, C.—IV-B-a-1, 2
TAYLOR, H. A.—III-A-20
TEASEL, R. C.—IV-C-5
THORPE, M. L.—IV-C-9, 10, 16; E-4
TORDA, P.—V-A-1, 2, 3; VI-B-2, 3
TRENT, C. H.—III-A-18, 22; B-3
TYLER, T. L.—IV-E-11
UBEROI, M. S.—II-C-25, 27; VI-C-13
VAWTER, F. J.—I-C-8
VILLALBA, I. P.—V-A-1
VON ELBE, G.—IV-A-2; B-a-8
VON ROSENBERG, H.—IV-B-b-10
WALTER, D. R.—III-A-1
WARNER, C. F.—II-C-17; V-C-2
WARREN, W. R.—II-C-26, 30
WEATHERSTON, R. C.—V-A-6
WEIL, C. W.—IV-B-b-10
WEISS, W. I.—VI-B-1, 2, 3
WELLS, F. E.—IV-B-b-9
WELTY, F.—IV-D-4
WHATLEY, A. T.—III-A-24, 25
WILDER, J. G.—V-B-2, 10; VI-C-1
WILLIAMS, G. C.—IV-C-13; E-10
WINNING, W. I. H.—III-A-23
WITT, R. H.—I-C-4
WOHL, K.—IV-B-b-10, 11; D-4; E-6, 8
WOO, P. T.—IV-C-22
WOOD, H. L.—IV-A-3
WOODY, M. W.—IV-C-8
YEARIAN, H. J.—I-C-10, 12, 15
YUAN, S. W.—II-A-1, 2, 3, 4, 5, 16, 18
ZUCROW, M. J.—II-C-17, 21; III-A-18–22; B-3; V-C-2, 4

Rockets Aweigh



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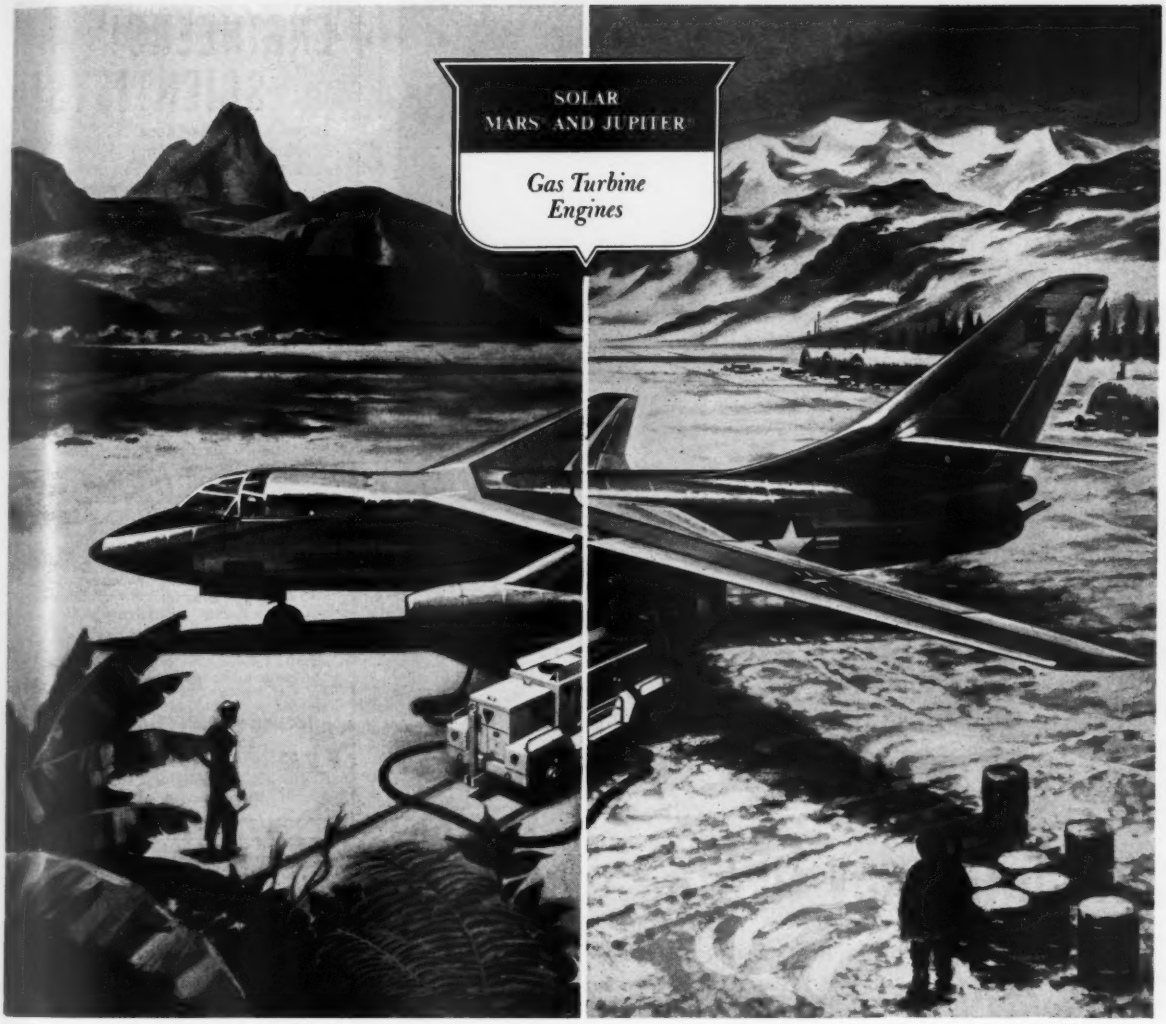

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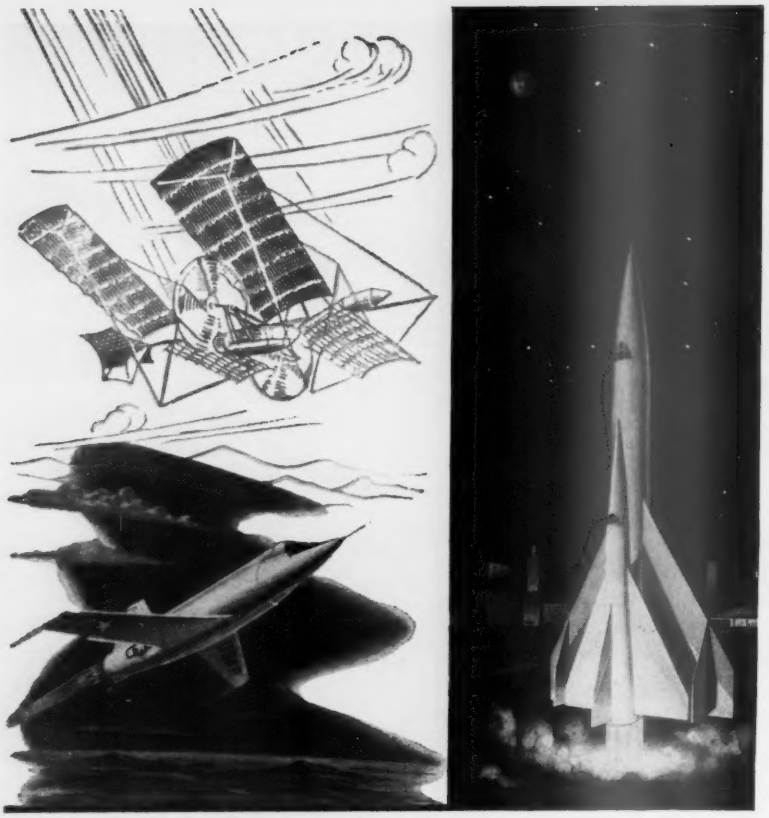

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Japanese Guided Missiles in World War II[1]

MARTIN CAIDIN[2]

WORLD War II produced many new types of weapons, several of which have effected revolutionary changes in the nature of combat. These include a host of aerial innovations, radar, proximity fuses, automatic computers, shaped charges, and so on. Outstanding among them all, however, are two particular weapons which have widened the scope of war: the operational guided missile and the atomic bomb. Both weapons involve such radical departures from "accepted" means of offense and defense that they require an entirely new concept of armed internal conflict.

Germany began her guided missile research in prewar days and, during the war, introduced and used many and varied types of missile weapons. These included the Henschel Hs 293 series, the Fritz X, Rheintochter, Schmetterling, Wasserfall, V-1, V-2, and others. Germany clearly led the world in missile development and utilization. The United States, however, engaged in considerably more missile work than has been generally realized. In free-falling bombs, the Americans developed a series of weapons which included Azon, Razon, and their successors; at Rabaul they tested Felix heat-seeking bombs. In 1943 the familiar B-17s launched hundreds of GB-1 glide bombs against Cologne, and improved models of these bombs finally were used.

As the war neared its end, Japanese ships frequently encountered the Bat, radar-homing glide bomb. Fighter planes were converted into radio-controlled, television-guided "bombs."

England tested experimentally a few ground-to-air and air-to-ground, radio-controlled guided missiles, but these were of little significance in the over-all war picture.

It is not commonly known that during the latter stages of World War II Japan rushed the development of the guided missile for tactical purposes. The Oka, Kikka, Shinryu, Baika, Tsurugi, and Toka were all piloted suicide bombs which glided, or were powered by rockets, jets, or piston engines, to their targets. Remote-guided bombs were developed also for use against American warships and aircraft. The following descriptions pertain to these guided missiles. All organizations referred to are Japanese.

1 Aircraft Launched Anti-Ship Radio-Controlled Guided Missiles

In the spring of 1944 the Japanese Air Research and Development Center, Army Bureau of Aeronautics, commenced research activities for a missile to be employed against enemy surface ships. By July, the Bureau had crystallized its many proposals into the design requirements for two specific classes of rocket propelled, airplane-type guided missiles, the I-go Model 1A and the Model 1B (Figs. 1–4). Engineer Major Takeo Omori of the Army Air Research and Development Center received the assignment of preparing the basic layout of the stabilization devices and the radio-control system and of directing the actual missile tests. The Army assigned the airframe design and fabrication work for the 1A to Mitsubishi, and for the 1B to Kawasaki; Mitsubishi also was ordered to prepare the rocket engines for both missile types.

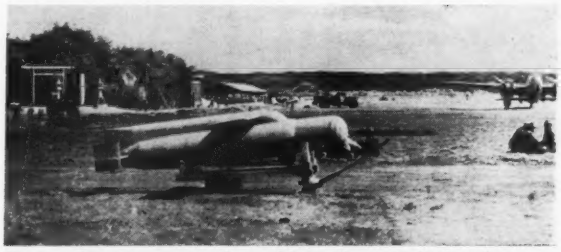

Fig. 1 Japanese army air-to-ship radio-controlled rocket propelled guided missile I-go Model 1B

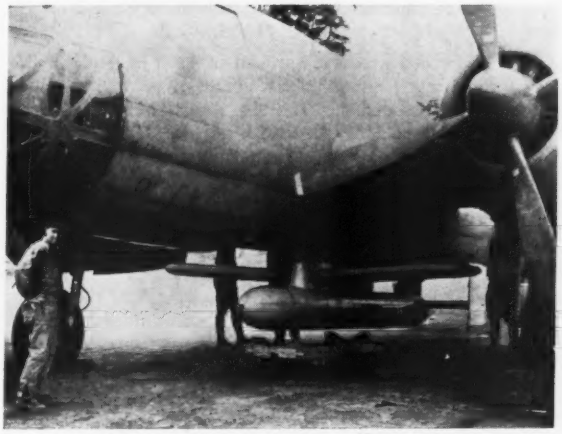

Fig. 2 Japanese army air-to-ship radio-controlled rocket propelled guided missile I-go Model 1A

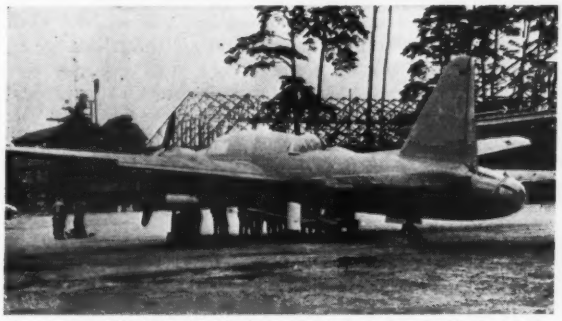

Fig. 3 I-go Model 1A missile mounted under the belly of the mother plane Peggy bomber

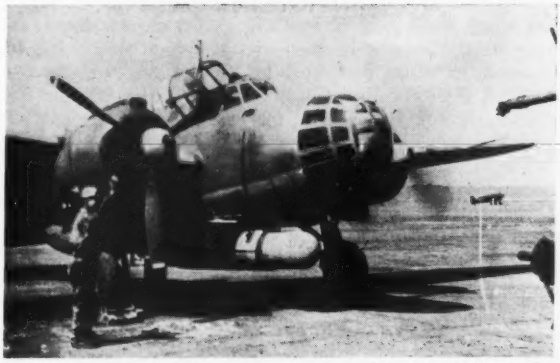

Fig. 4 I-go Model 1B missile mounted under the belly of the mother plane Lily bomber

[1] The material on the Japanese guided missile program was assembled by the author during work with Jiro Horikoshi, chief engineer for Mitsubishi Heavy Industries, Ltd., and the designer of the famed Zero and other fighter planes; and Colonel Masatake Okumiya, former Naval Commander, and today the Chief of Intelligence, Joint Chiefs of Staff, Japan Defense Forces.

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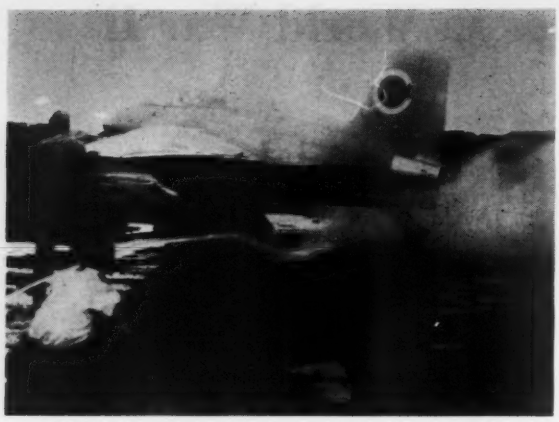

Fig. 5 Japanese navy rocket interceptor Shusui

The 1A carried a Navy warhead of 1760 lb, and the 1B a 660-lb armor-piercing nose bomb. The twin-engined bomber Peggy carried the 1A aloft (Figs. 2 and 3); the Lily transported the 1B (Fig. 4). Both missiles were designed to be launched from the mother airplane at a point 6.8 miles from the target at an altitude between 2300 and 3000 ft. Thereafter the missile sustained flight through use of its rocket engine; the mother plane, now acting as the director, followed the missile's flight until the bomber was 2.5 miles from the target. The bombardier in the nose of the directing plane tracked the distance from the target and the line of flight with an optical sight, visually controlling the missile by radio to hit the objective.

Army engineers and engineers from Mitsubishi's Nagoya Engine Research Division and Nagasaki Ordnance Works coordinated their efforts to produce the rocket engines. These used concentrated hydrogen peroxide as the propellant and an aquatic solution of sodium permanganate as the catalyzer. The construction and control systems of the engine were rather simple; the propellant and catalyzer were fed under the pressure of compressed air (initial charge of 150 atm or 2200 psi). The stabilizing system comprised one position gyro which controlled the elevators and ailerons; the radio signals from the directing plane controlled the elevators and rudder; in the 1B series, the rudder and ailerons were coordinated by a special linkage system. In the 1A series, pneumatic power was used for driving the gyro and the operating control surfaces; equipment for this purpose was developed and manufactured by the Tokyo Aircraft Instrument Company. The electrical system used for gyro and control surface power in the 1B series was produced by the Sumitomo Communicating Machine Company in collaboration with the Hokushin Electric Works, Ltd. Sumitomo also developed the radio-control system for both missiles.

In a later development the Army attempted to eliminate the longitudinal control system. Sumitomo produced an experimental automatic radio-control system which was to maintain an altitude of from ten to thirty feet above sea level. Unfortunately the Japanese never learned whether the equipment would function satisfactorily; the incessant air raids suspended all tests by the summer of 1945.

The Mitsubishi design team which produced the Peggy bomber and also developed the 1A series was headed by engineer Hisanojo Ozawa. For the missile Ozawa used a simplified construction of wooden wings and empennage, some wooden accommodations, and a fuselage of galvanized sheet iron. The company delivered ten to the Army by November of 1944. The Army soon received several of the production missiles turned out by the Nippon Rolling Stock Company, and submitted the new weapons to their first drop tests at Point Manazuru, near Atami City, Izu Peninsula, Kanagawa Prefecture. The second series of tests was held at Lake Biwa and at Wakasa Bay, near Maizuru City, facing the Japan Sea. By the time the Army concluded its drop tests, they were able only to complete the adjustments of the control surfaces and the stabilizing and control systems. As the single pneumatic power source was utilized for feeding the propellant to the combustion chamber, operating the gyro, and actuating the servos, the air pressure for the latter dropped sharply at the close of the rocket propelled flight. It was anticipated that better flight characteristics could have been attained after remedying this effect.

Kawasaki assigned engineer Jun Kitano as chief engineer for the design of the 1B airframe series. Approximately one hundred and fifty 1B models were built; these underwent Army drop tests from November of 1944 to July of 1945. The first launching and gliding test at Ajigaura, Ibaraki Prefecture, gave promising results. Until February of 1945 the Army held its second series of flight tests at Point Manazaru where gliding, powered flight, and preliminary radio-control tests were conducted. The third and fourth test series continued until July, during which time the engineers improved the stabilizing and control systems and confirmed the accuracy of hits. These latter experiments were held at the Yokaichi Army Air Field, Shiga Prefecture. The Army used the prominent Shiraishi rock in Lake Biwa as its target. The results indicated that the missile was assured of success in combat, that the radio-control system was perfectly adequate and that, with or without power, the flight characteristics were satisfactory. The test group estimated an accuracy of seventy-five per cent in hits against aircraft carriers and battleships.

The Army had developed its 1A and 1B missiles for a specific purpose. They were intended for use against enemy aircraft carriers which were at the center of a ring formation providing heavy AA protection and fighter plane screens. The missiles proved successful in the experiments, but the Army was convinced that their relatively low performance, even were it improved, would not permit the launching plane to survive the enemy's deadly defense system. For this reason, and also because further factory work was disrupted by the incessant B-29 attacks, the Army suspended the project.

Table 1 I-go missiles Models 1A and 1B

	1A	1B
Configuration	High-wing monoplane	High-wing monoplane
Construction	Wooden wings and empennage; galvanized sheet iron fuselage	
Power plant	Special rocket no. 1 Model 3	No. 1 Model 2
Thrust × duration	530 lb × 75 sec	330 lb × 80 sec
Propellant	Concentrated hydrogen peroxide; aquatic solution of sodium permanganate	
Maximum speed (est.)	342 mph	342 mph
Launching speed	224 mph	224 mph
Principal dimensions		
Wingspan	11.8 ft	8.52 ft
Length	18.9 ft	13.4 ft
Height	3.46 ft	2.95 ft
Wing area	38.8 sq ft	21.0 sq ft
Weight, loaded	3085 lb	1500 lb
Warhead	1760 lb HE	660 lb AP
Date of completion	Nov. 1944	Oct. 1944
Final disposition	Preliminary test phase	Almost completed

2 Guided Missile Research, Army Technical Research Institute

Infrared Ray Automatic Homing Air-to-Ground Missiles

The Technical Research Institute, Army Bureau of Ordnance, conducted special research into infrared ray automatic homing air-to-ground missiles, working with Itogawa's laboratory of the Aeronautical Research Institute, Tokyo Imperial University. The Army group conducted preliminary experiments with its new homing device in the summer of 1945 at Lake Hamana, Shizuoka Prefecture, using a bonfire on a raft as the target. The experimental gliding missiles had a torpedo-shaped body of 1.64 ft diam and 9.9 ft length; wings were cruciform, 8.2 ft in span; and the empennage as well was cruciform.

The aerial torpedoes were released by a mother plane. In the nose of the missile the Army installed a parabolic reflector to collect heat radiation from the target, with a heat-sensing bolometer located at the reflector's focal point. The principle of homing was to make use of the fluctuation of electric current caused by the heat energy received by the sensing unit, and to amplify the current to actuate the servo mechanism which operated the control valves of the pneumatic actuators for the control surfaces. Prior to the experiments, the Army felt that the homing system would lack accuracy in daylight attacks because of the reflection of solar heat by the ocean surface. The experiments conducted at night, however, indicated fairly good homing characteristics once the missile caught its target. The system appears to have excellent possibilities for future development.

The Shusui Missile

The Institute also planned for the conversion of the piloted rocket interceptor Shusui (the Japanese version of the Messerschmitt Me-163B Komet) to a high speed missile guided along a radio-wave beam for use against enemy ships or large aircraft (see Fig. 5). The guidance system, developed by Major Masahiko Okamoto and other engineers, comprised two VHF beams, along the equi-intensity line of which the missile would be guided with a directional accuracy of plus or minus 0.5 deg, and with an effective range of at least ten thousand feet. By the end of the war the guidance system was nearly complete. Preliminary tests were held in July of 1945 when the beam was directed from Chosi, Chiba Prefecture, to Mount Tsukuba, Ibaraki Prefecture, along which the pilot of a Type 99 light bomber (Lily) was almost successfully guided.

3 Ground-to-Air and Ground-to-Ship, Radio-Controlled, Rocket Propelled Guided Missiles

Development

From 1943 the Technical Research Institute, Naval Technical Bureau, had conducted research into RATO and rockets for aircraft, and investigated propellants and liquid-fuel rocket motors for propulsion of special submarines and new-type torpedoes. In the summer of 1944 the Institute began research work on a rocket propelled anti-shipping guided missile which employed a radio-impulse (modulation of medium frequency carrier wave) command guidance system which the Navy originally had developed for controlling target vessels. As the B-29s began raids on northern Kyushu from bases in China, the Institute, in September 1944, changed its program to the development of anti-bomber missiles. These experimental weapons were at first called the "Special Rocket Propelled Missile," but the designation was later changed to Funryu (raging dragon).

Three anti-bomber missile types were designed and built, only the first of which underwent preliminary tests. They were generally similar in shape; each had a torpedo-like body, was gyroscopically stabilized, and had cruciform stubby wings and cruciform empennages. These missiles were the:

Funryu Model-2. For preliminary launching and guiding tests. Powder rocket propelled and guided by the afore-mentioned guidance system.

Funryu Model-3. Similar to Model-2 except for replacement of the solid-fuel motor with the liquid-fuel motor developed at the Institute.

Funryu Model-4. Considerably larger than the Model-2 and -3. Liquid rocket engine, propelled and guided by an automatic command guidance system consisting of two radar sets and a mechanical computer.

Ten of the Model-2 missiles were airborne from a rail launcher set up on a hill near Asama Meadow, Kitakaruizawa, near the border of Nagano Prefecture and Gunma Prefecture; the missiles were directed against a point on the shoulder of Mt. Asama. Tests beginning in April of 1945 were continued for several months.

Engineers regarded the Model-2 as a failure and, consequently, also abandoned further work on the Model-3. They now concentrated all their efforts on the larger Model-4. Navy staff officers and civilian company engineers set up emergency quarters in a hotel at Atami, where they rushed through the final designs of the new missile. Although the manufacture of the airframe and the guidance system had barely gotten under way when Japan capitulated, two of the rocket motors (one by Nagasaki Ordnance Works of Mitsubishi Heavy Industries, Ltd., and the other by the Institute) were completed. The ground tests for the new engines were scheduled for August 16, the day following the surrender.

The results of the launching and guidance tests of the Model-2, with and without the guidance system installed (but with weight compensations and adjusted CG), are summarized:

Maximum range of 18,000 ft was obtained when the missile was launched at an elevated angle of 45 deg. Stability and controllability characteristics, in pitch and yaw, were satisfactory. The poor stability in rolling, especially at the slow speeds encountered after launching, prevented accurate guidance.

In March of 1945 the Jet and Rocket Propulsion Research Division was established within the Institute specifically to coordinate missile development. Many additional Navy and industrial facilities contributed to this work, as listed below:

Electronics Division, Technical Research Institute	Guidance systems
NARDC	Wind tunnel experiments
Naval Dockyard, Yokosuka	Airframe manufacture
Naval Powder Arsenal	Powder rockets
Aeronautical Research Institute, Tokyo Imperial University	Airframe design; analysis of performance and stability for Model-4. Designed stabilization units for all models
Nagasaki Ordnance Works, Mitsubishi Heavy Industries, Ltd.	Design and manufacture of propulsion unit for Model-4
Kawasaki Aircraft Industry Co.	Airframe design for Model-4
Tokyo Aircraft Instrument Co.	Design and manufacture of the stabilizing units for all models
Technical Research Institute, Nippon Broadcasting Assoc.	Guidance system (conducting flight tests)

Features of the Funryu Models 1–4

Model-1. Anti-shipping, liquid rocket propelled missile. The airframe, propulsion, stabilizing, and servo systems were very similar to those of the Model-4; the guidance system was patterned after that of the Model-2. This project was discontinued after the preliminary layout was completed because of the changing war situation which called for measures to stop the B-29s.

Model-2. For preliminary testing; anti-bomber, powder rocket propelled missile. The powder rocket used a cordite propellant and provided a maximum thrust of 5300 lb for a duration of 3.5 sec. The guidance system was adapted from the control system for target vessels. The operator on the ground, sighting the missile and the target, operated the control transmitter which sent out radio command signals (modulation of medium-frequency carrier wave) which actuated the corresponding electrical relays of the missile (for maneuvers in up, down, left, or right directions). The relays operated valves of the pneumatic servo system which in turn operated the control surfaces.

The transmitter carried in the missile sent a response signal to the ground station every time a command signal was received. All control surfaces operations were recorded by an auto-recorder carried in the missile.

The stabilizing unit consisted of two sets of compressed air-driven gyros which automatically governed the control surfaces. The engineers used a laminated dry cell for the missile's electric power source.

Over-all length	7.87 ft
Wingspan	3.15 ft
Diameter	0.985 ft
Gross weight	815 lb
Warhead	110 lb
Maximum speed (est.)	790 fps
Maximum altitude (est.)	16,400 ft

Model-3. Anti-bomber, liquid rocket propelled missile, identical to the Model-2 except for replacement of the propulsion unit with the liquid-fuel rocket motor. One model was built, but was not flight tested.

Model-4. Anti-bomber, liquid rocket propelled missile. The general configuration, although considerably larger, resembled closely that of the Model-2. The rocket motor was designed from the German Walter unit and used two propellants, 80 per cent hydrogen peroxide and a mixture of methyl alcohol and hydrazine hydrate. Propellants were fed to the combustion chamber by compressed air or nitrogen. The thrust of 3300 lb was maintained for 60 sec.

Except for the servo system, the guidance system was a development separate from that of Models-1, -2, and -3. Ground equipment included two radar sets and a mechanical comparator computer. The first radar tracked the target, while the second radar tracked and transmitted control signals to the missile. Data from the two sets led into the computer where corrections for the missile path were calculated and relayed back to the second radar. The latter sent out five specific types of control signals (according to the information it received from the computer) to the missile, which included up, down, right, left, and explosion. For tracking, VHF wave was employed, and for transmitting the control signals (command), frequency modulation of the VHF carrier wave.

The effective guidance range was estimated at 12 to 18 miles, and the error in the missile path to be within 0.5 deg or 50 m (164 ft). The stabilizing and servo system was almost similar to that of the Model-2.

Over-all length	13.1 ft
Wingspan	5.25 ft
Diameter	1.97 ft
Maximum speed (est.)	0.9 Mach
Maximum altitude (est.)	82,000 ft
Time for climb to 32,800 ft	1 min
Gross weight	4190 lb
Warhead	440 lb

4 Guided Missile Research, Aeronautical Research Institute

Radio-Controlled Small Target Plane

From 1940 to 1943 the Itogawa Laboratory of the Aeronautical Research Institute, Tokyo Imperial University, conducted research on radio-controlled small target planes. Initial studies were aimed at stability and controllability through model flight tests. Later, when Satoshi Narita of the Noborito Laboratory joined the project, emphasis was shifted to a practical-use target plane. Two experimental models were built, one with a single engine of $^1/_2$ hp, and the other with two $^1/_2$ hp engines and a wingspan of 8.2 ft. The models successfully passed their flight tests and could execute figure-eights and loops.

Anti-Bomber Missile Guided by Radio Beam

Work on an anti-bomber missile guided by radio beam began in 1943 as the war situation deteriorated. The first method of guidance used was a radio-beam system, in which a 200 MC carrier wave was modulated by 3 to 10 KC and revolved around an axis.

The small test missile employed had a torpedo body with small cruciform wings and cruciform tailplane. A special air-cooled, four-cylinder, two-stroke cycle, opposed-type engine of 20 hp was designed for the test model. The airplane was released and directed by a mother plane to the target. Twenty test missiles were built, but only a few of these were employed for fundamental research in stability, guidance, performance, and so forth. The project did not develop beyond the preliminary stages.

Aircraft-Launched Anti-Shipping Automatic Homing Glide Missile, I-go Model 1C

Research on the I-go Model 1C was started in the spring of 1944. The missile steered itself in the direction normal to the surface of shock waves sent out by the gunfire of the enemy ship; its trajectory would automatically converge to the target, in this case the firing gun. The first step in the new project was to investigate thoroughly the characteristics of the shock waves emitted by heavy guns. The Aeronautical Research Institute conducted most of the preliminary experiments, using the peak of the main building's tower as its measuring site.

The preliminary tests revealed two promising homing methods. One utilized the minute time lag between the wave fronts reaching each wing tip for determining the direction of control. The other method incorporated a horn with directional characteristics and a microphone which sensed the higher acoustic harmonics (3000–5000 cps) of the shock wave emitted from the target. Both methods were subjected to exhaustive experimentation.

The latter method was finally accepted as the most promising. A torpedo-shaped experimental missile (1.64 ft in diam and 11.5 ft in length) with cruciform wings and empennage was equipped with a gyro stabilizing system, shock wave (direction) sensing unit, automatic steering devices, and a speed-brake system. In the steering system built especially for the test missile the Laboratory selected as its final arrangement solenoid actuators for three primary controls, and a torque motor for the speed brake. A 36 v, 60A injection cell was used for the electric power source.

The greatest obstacle to be overcome was inadvertent rolling, and hundreds of wind tunnel tests were required to find the satisfactory solution. On the other hand, it was discovered that the amplifiers comprised some twenty vacuum tubes, which involved the necessity of selecting two hundred-odd satisfactory tubes out of a thousand for ten drop tests. Obtaining a sufficient quantity proved to be one of the major problems.

In March of 1945 three missiles were launched from a Peggy bomber at the Kujihama Bombing Test Ground near Mito Air Base. The results confirmed the expected converging motion of the missiles, proving the reliability of the new homing device. The successful tests resulted in support from the Army Bureau of Aeronautics, and twenty improved experimental missiles were produced by July. Following the Kuji-

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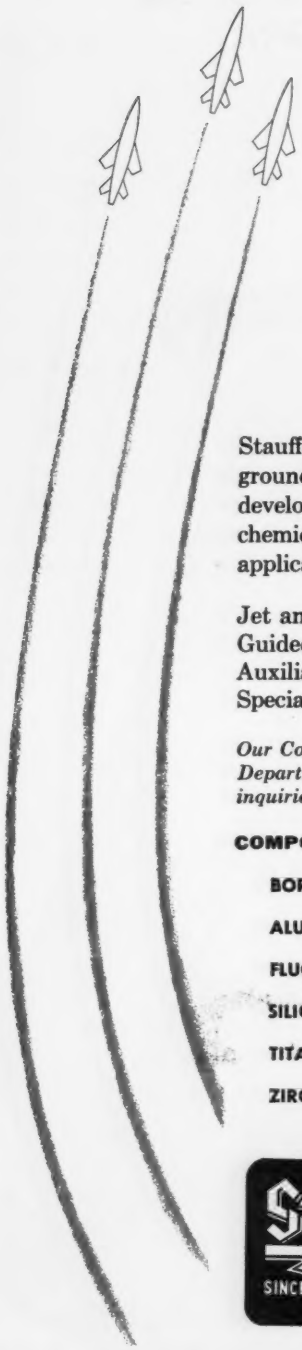

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hama experiments, a neutral position was provided for each of the primary controls. Six gyros (position and rate gyros for each of the three axes) were installed, as against the one gyro for preventing rolling motion in the original models.

The first six missiles were dropped from a Lily bomber at Lake Biwa to confirm the functioning of the new gyro-stabilizing system; in these tests the shockwave-sensing automatic homing device was not used. The engineers jubilantly reported complete success. However, when the group was about to begin its drop tests with the fourteen fully equipped missiles, the constant air raids destroyed important equipment, hampering the projected experiments. As the engineers prepared to move the testing grounds to Akita Prefecture, the war ended.

5 Radio-Controlled Aircraft and Target Plane

The Navy's target planes for antiaircraft training were pioneered by the glider target MXY3, adopted in 1938. (MX identifies special airplane; Y the NARDC's design.) The MXY3 was an all-wood, high-wing monoplane. The Type 94 reconnaissance seaplane (Alf) released the target glider from a dorsal rack. After its introduction for fleet use, engineers added an air-driven gyro to maintain constant headings.

As early as 1937 the Naval Aircraft Establishment (later the NARDC), commenced work in secret on the development of equipment which permit remote radio-control of aircraft. In 1939 engineers and pilots held joint conferences where they discussed the radio-control application for pilotless bombers, torpedo-bombing aircraft, decoy planes, and target planes for antiaircraft training. In September 1940 and in the spring of 1941 the combined efforts of the Electric, Instrument, and Aircraft Divisions of the NARDC showed remarkable success in the radio-control experiments with the Alf seaplane. These included catapult operations, climbing, level flight, turning in flight, and landing. Despite the success of the experiments they were not pushed further. The Navy estimated that the total cost of the radio-control equipment and the auto-pilot mechanism, as well as launching, exceeded by several times the cost required for training one pilot per plane. But, eventually, the experiments with the Alf stimulated work on a radio-controlled target plane, larger than the MXY3, which could float on water.

NARDC designed and built an all-wood, twin-float, low-wing monoplane to be carried by the Type 94 seaplane in the same fashion as the MXY3. The model was designed to allow elevator and rudder control, stopping the engine, and recovery parachute release, all from the mother airplane. The first tests were made in October of 1941 at Saeki Bay, Oita Prefecture, in Kyushu. The initial flight ended in failure because of elevator overcontrol, but this was remedied in the second model which proved successful in a sustained thirty-minute flight. This model became the Type 1 Target Plane Model 11 (MXY4) and was produced in quantity until the outbreak of war.

Wingspan	32.8 ft
Length	23.0 ft
Wing area	140 sq ft
Incidence	4 deg
Dihedral	6 deg
Gross weight	1125 lb
Engine (Nippon Internal Combustion Engine Co.)	Semi-11, or AVA 4H, 22 hp

The stabilizing and control systems comprised two sets of electrically driven rate gyros and electric gyros connected with the elevator and rudder control, respectively. The elevator also was controlled by the air-speed meter system, to maintain constant speed. The engineers ran into severe difficulties. Even minute differences in the fabrication of wings and control surfaces necessitated different adjustments of control and servo systems from plane to plane.

Notable Achievements at JPL

REALISM IN VIBRATION... Recognizing that it was necessary to provide a simulated missile-flight vibration environment far more realistic than heretofore available the Laboratory developed high power, wide-band, complex waveshape vibration testing equipment.

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Design and test for survival in adverse environment is fundamental in producing guided missile components with reliability adequate for modern weapons system requirements. At JPL, a constant search is being conducted for better design and packaging techniques, and for more significant laboratory test methods. Development of the "complex wave" vibration test philosophy, and of apparatus to exploit it, are but two results of this program. In the area of component design, new packaging techniques have been developed, involving control of local internal resonances and nonlinearities, which permit electronic circuits to withstand many times the vibration level which would destroy a conventional package.

Engineers and scientists are working at JPL in nearly all of the physical sciences. Here they are supported not only by outstanding laboratory facilities, but by a continuing series of experimental rocket firings which provide an invaluable tool for research and development.

The combination of a broad base of fundamental research, active development effort, and strong test and flight program has made the Lab a place of achievement. Perhaps you would like to participate in the many new, exciting programs now under way here. Your inquiry is invited.

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ARS News

Who's Who at Buffalo Meeting

Clifford Furnas

Frank Everest

William Smith

Harry Ferullo

Ralph Bloom

1956 Fall Meeting, Buffalo, Sept. 24–26

Background

NEXT month, Niagara Frontier Section will act as host for the ARS 1956 Fall Meeting at Buffalo. And the Section has come up with what promises to be one of the best national meetings yet.

As the schedule now stands, combustion, instrumentation, and propellants will get top billing as technical session topics. Tours, banquets, and exhibits will round out the agenda.

Almost sure to attract a wide audience are the special dinner and luncheons which will feature the following speakers (see photos): Assistant Secretary of Defense Clifford C. Furnas, former chancellor of the University of Buffalo and the man who is now responsible for the government's research and development program; Lt. Colonel Frank K. Everest, chief of Flight Test Operations Laboratory at Edwards Air Force Base where he is presently trying to push the Bell X-2 past the 2000 mph mark; and, tentatively, Leston P. Faneuf, vice-president and general manager, Bell Aircraft Corp.

Among others, those responsible for putting this program together (see photos) are: General Chairman Harry A. Ferullo, project manager, Bell Aircraft Corp.; Program Chairman Ralph Bloom, Becco Chemical Div., Food Machinery and Chemical Corp.; Section President William M. Smith, chief rocket engineer, Bell Aircraft Corp.

Program

GENERAL INFORMATION

Registration will take place from 8 a.m. to 5 p.m. Monday morning in the Hotel Statler which has been chosen as convention headquarters. At this time, members should also make arrangements for luncheons, banquets, and tours they wish to take part in.

There will be no registration charge for ARS or ASME members, military personnel, or students. Others must pay a $5 fee.

Trips: There will be a tour of Niagara Falls starting Monday evening at 7:30 p.m. In order to cross to the Canadian side, naturalized U. S. citizens must show citizenship papers; aliens, visas.

A field trip to the Nike facility on Grand Island is scheduled for 1:30 p.m., Sept. 26. Confidential clearance will be required. (A clearance form will be found in each meeting program.)

Dining arrangements are scheduled as follows: Authors' Breakfast, 8–9 a.m., Sept. 24, 25, and 26; Luncheons, 12:30–2 p.m., Sept. 24 and 25; Banquet, 7 p.m., Sept. 25.

All exhibits will take place at the Hotel Statler. Among those tentatively planning displays are: Bell Aircraft Corp., Carborundum Co., Conax Corp., Cornell Aeronautical Laboratory, Inc., Ford Instrument Co., General Electric's Aircraft Gas Turbine Div., Kistler Instrument Co., North American Aviation, Inc., Potter Aeronautical Co., Reaction Motors, Inc., R. L. Schwartz, Scott Aviation Corp., and Thompson Products, Inc.

Movies from various aircraft and rocket companies are slated to run on the mezzanine of the Hotel Statler at the same time as the technical sessions. They will be open to those not attending portions of the technical sessions.

TECHNICAL SESSIONS

Monday, Sept. 24

9:00 a.m. General I

Chairman: Thomas F. Reinhardt, Section Leader, Bell Aircraft Corp.

Vice-Chairman: John D. Clark, Head of Liquid Propellants Section, U. S. Naval Air Rocket Test Station.

✦ Stability Criteria for the Injection of Liquid Films, by Bruce A. Reese and Cecil F. Warner, Purdue University. (312–56)

✦ Some Considerations of Film Cooling for Rocket Motors, by Alfred R. Graham and Maurice J. Zucrow, Purdue University. (313–56)

✦ Upper Bounds for the Aerodynamic Heating of an Ascending Rocket, by J. Friedrick Vandrey, Glenn L. Martin Co. (314–56)

✦ The Recovery of High Speed Rocket Powered Vehicles and/or Their Components, by Robert Provart, Cook Research Laboratories. (315–56)

✦ Prediction of Ram Jet Performance on the Basis of Minimum Spark Ignition, by Hartwell F. Calcote, Experiment, Inc., and John B. Fenn, Princeton University. (316–56)

12:30 p.m. Luncheon

Speaker: Leston P. Faneuf (tentative), vice-president and general manager, Bell Aircraft Corp.

Master of Ceremonies: J. H. van Lonkhuyzen, chief, Technical Dept., Bell Aircraft Corp.

2:00 p.m. Combustion

Chairman: George H. Markstein, principal physicist, Cornell Aeronautical Laboratory, Inc.

Vice-Chairman: John B. Fenn, director, Project Squid, Princeton University.

✦ Survey of Proposed Scaling Procedures for Liquid Fuel Rocket Engines, by S. S. Penner, California Institute of Technology. (317–56)

✦ Similitude Concepts in Rocket and Jet Engines (tentative title), by S. Way, Westinghouse Electric Co. (318–56)

✦ The Structure of Chlorine Flames, by R. F. Simmons and H. G. Wolfhard, RAE Rocket Propulsion Dept. (319–56)

✦ Flame Stabilization in a Boundary Layer, by H. C. Hottel, T. Y. Toong, and J. J. Martin, Massachusetts Institute of Technology. (320–56)

✦ Rotating Flame Stabilizer, by J. H. Grover, M. G. Keeler, and A. C. Scurlock, Atlantic Research Corp. (321–56)

Tuesday, Sept. 25

9:00 a.m. Instrumentation

Chairman: Walter Kistler, president, Kistler Instrument Co.

Vice-Chairman: Iben Browning, Bell Aircraft Corp.

✦ Accurate Accelerometer Testing, by John Amico, Bell Aircraft Corp. (322–56)

✦ A New Piezo-Electric Gage for Measurement of Thrust, Static and Dynamic Pressures, by Robert W. Lally, Kistler Instrument Co. (323–56)

✦ Shock Tube Research, by William Smith, Cornell Aeronautical Laboratory (324–56).

✦ The Advantages of Consolidated Test Equipment, by Robert A. Shea, Allen B. DuMont Laboratories. (325–56).

✦ A Method of Optimizing Instrumentation Systems for Rocket Testing, by J. W. Zimmerman, Rocketdyne Div., North American Aviation, Inc. (326–56)

✦ Fast Response Temperature Measuring Instrumentation, by R. Vidal, Cornell Aeronautical Laboratory. (327–56)

12:30 p.m. Luncheon

Speaker: Lt. Col. F. K. Everest, Jr., chief, Flight Operations Laboratory, Edwards Air Force Base.

Master of Ceremonies: Roy Sandstrom, vice-president, engineering, Bell Aircraft.

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2:00 p.m. Propellants

Chairman: D. N. Griffin, Olin Mathieson Chemical Corp.
Vice-Chairman: H. F. Calcote, Experiment Incorporated.

✦ Field Handling and Transport of Concentrated H_2O_2, by John H. Keefe and Charles Raleigh, Becco Chemical Div., Food Machinery and Chemical Corp. (328–56)

✦ The Physical and Chemical Properties of the Alkyl Hydrazines, by R. C. Harshman, Olin Mathieson Chemical Corp. (329–56)

✦ Unsymmetrical Dimethyl Hydrazine as a Starting Fluid for Nitric Acid Oxidizer and Jet Fuel Rocket Engines, by H. W. Byington and R. L. Potter, Bell Aircraft. (330–56)

✦ Chemical Aspects of Hypergolic Ignition for Liquid Propellant Rocket Engines, by Louis R. Rapp and Murray P. Strier, Reaction Motors, Inc. (331–56)

7:00 p.m. Banquet

Speaker: Clifford C. Furnas, Assistant Secretary of Defense for Research and Development.
Toastmaster: ARS President Noah S. Davis, manager, Special Projects, Becco Div., Food Machinery and Chemical Corp.
Master of Ceremonies: William M. Smith, chief rocket engineer, Bell Aircraft Corp.

Wednesday, Sept. 26

9:00 a.m. General II

Chairman: Rudolph Reichel, development engineer, Bell Aircraft Corp.
Vice-Chairman: Elliot Weinberg, chemical engineer, Becco Chemical Div., Food Machinery and Chemical Corp.

✦ Simulated Training for Rocket Powered Aircraft, by J. N. Pecoraro, U. S. Naval Training Device Center. (333–56)

✦ Powering the Vanguard First Stage, by H. M. Weber, General Electric Co. (334–56)

✦ Development and Manufacturing Problems of the Nike Thrust Chambers, by Joseph R. Piselli, Bell Aircraft Corp. (335–56)

✦ Explosive Operated Valves for Guided Missiles, by M. W. Connel, Conax Corp. (336–56)

✦ A High Intensity Sound Chamber to Imitate Rocket Noise, by Werner Fricke, Bell Aircraft Corp. (337–56)

1:30 p.m.

Trip to Grand Island Nike Facility.

Sections

Alabama: On May 3, 150 Section members and guests listened to Ernst Stuhlinger of Redstone Arsenal discuss interplanetary travel with nuclear-powered space ships. Using slides, Dr. Stuhlinger described a hypothetical trip to Mars by means of a nuclear-powered earth satellite.

At its following meeting, one week later, Darrell C. Romick of Goodyear Aircraft Corp. spoke to the Alabama Section on the dawn of the space flight age.

New York: A talk on the observation program for the earth satellite given by Fred S. Whipple, chairman of Harvard University's Department of Astronomy and director of Smithsonian Institute's Astrophysical Observatory, highlighted the Section's May 18 meeting. In his talk, Dr. Whipple underscored the importance of observations of the satellite made during the initial upward and final descent stages of flight. More advanced knowledge of the earth's upper atmosphere, surface configuration, and over-all shape, concluded Dr. Whipple, will result from this observation program.

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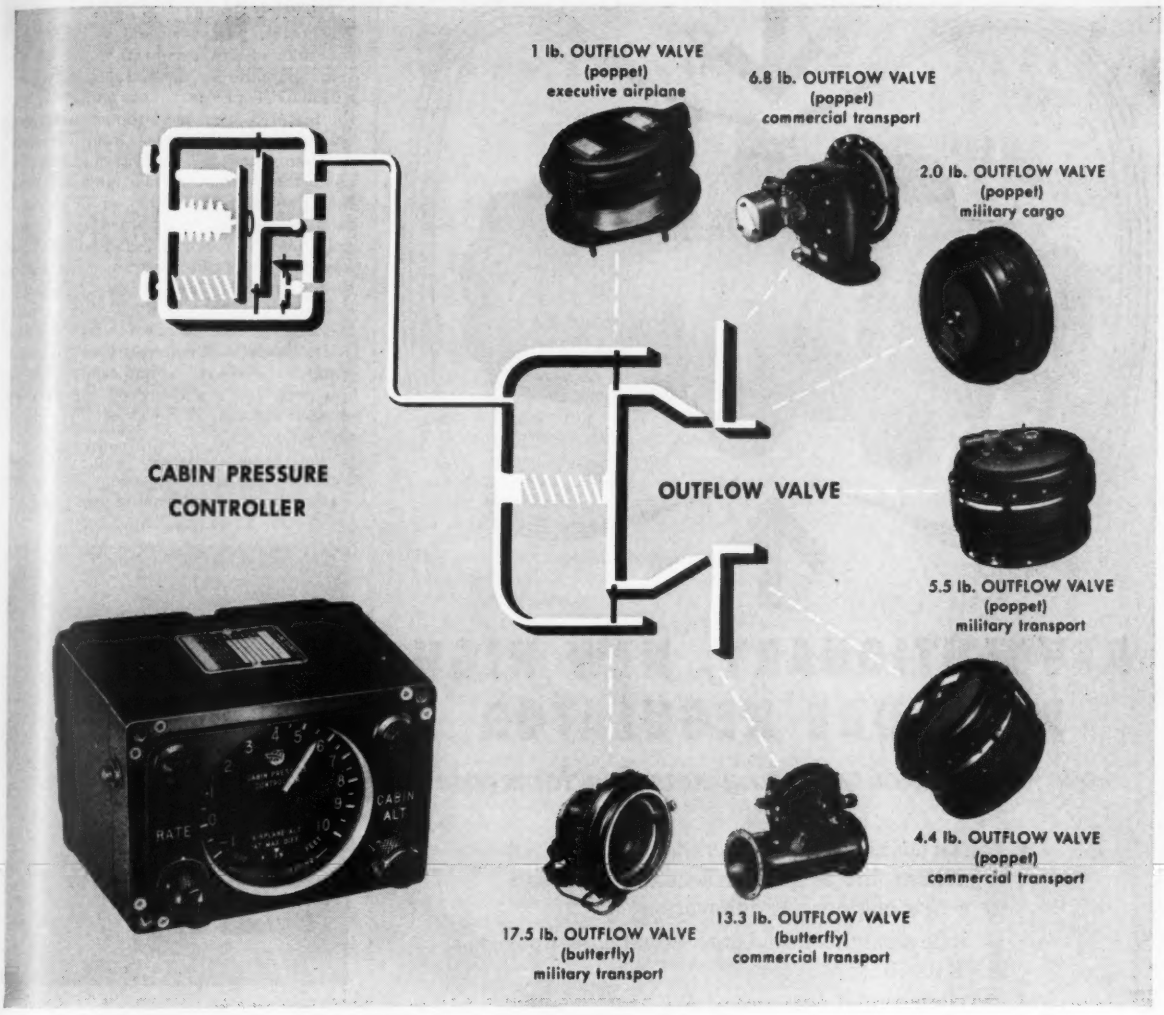

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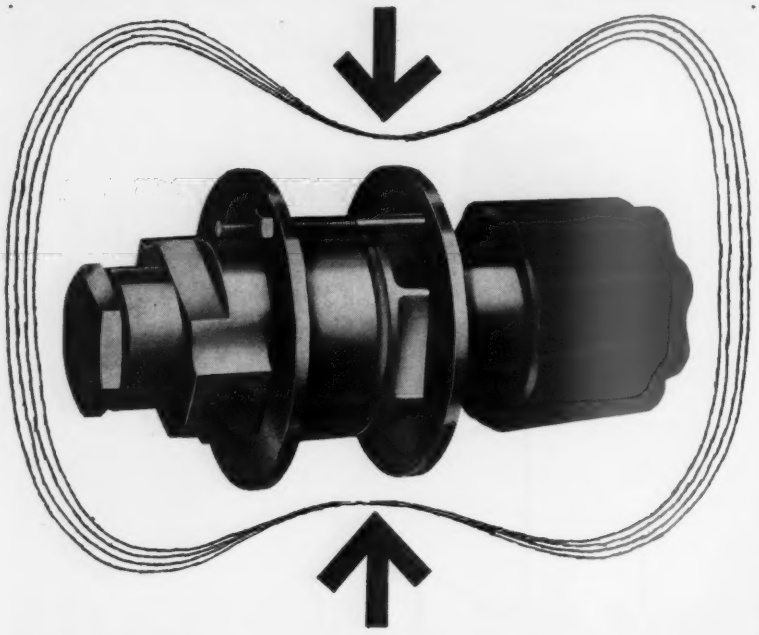

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Princeton Group: On June 2, Richard W. Porter, past president of ARS and chairman of the Technical Panel on the Earth Satellite for the forthcoming International Geophysical Year program, was the featured speaker at the annual group banquet. Introduced by Group President J. Preston Layton, Dr. Porter talked first about the International Geophysical Year, then discussed the history of U. S. earth satellite vehicles, experiments the program aims to carry out, and some of the implications of the program with regard to law, medicine, and religion.

Preceding Dr. Porter's talk, Kurt Stehling, Richard W. Foster, and William J. D. Escher—all connected with Project Vanguard—offered a humorous skit on the projected launching of the satellite as seen through the eyes of TV camera and announcer.

At the close of the meeting, Jerry Grey took over the group presidency from Mr. Layton for the forthcoming year.

Do-It-Yourself Rocket

Joel Singer, program chairman of the Arizona Section, shows his model MARS-XR-1 (Made by AMERICAN ROCKET SOCIETY—Experimental Rocket No. 1). Working at Hughes Aircraft's Tucson plant, Mr. Singer didn't have to wander far afield to find his hobby project.

As for the full-scale rocket, describes the builder: It would stand 200 ft high, measure 24 ft in diameter. Designed for leaving earth's gravity, the vehicle would use its wings as huge fuel tanks, jettison them when empty. Rocket motors in main cylinder would likewise be jettisoned as fuel is consumed. For support at take-off, wings would have their own rocket boosters.

ARS Meetings Calendar

Sept. 17–21: Seventh International Astronautical Congress, Palazzo dei Congressi, Rome. Space flight.

Sept. 17–21: Annual Meeting and Exhibition, Instrument Society of America, New York, including ARS session on satellites.

Sept. 24–26: ARS Fall Meeting, Hotel Statler, Buffalo (see p. 699).

Nov. 26–29: ARS-ASME Annual Meeting, New York. General subjects. (Manuscripts due Aug. 27; to Andrew G. Haley, 1735 DeSales St., Washington 6, D. C.)

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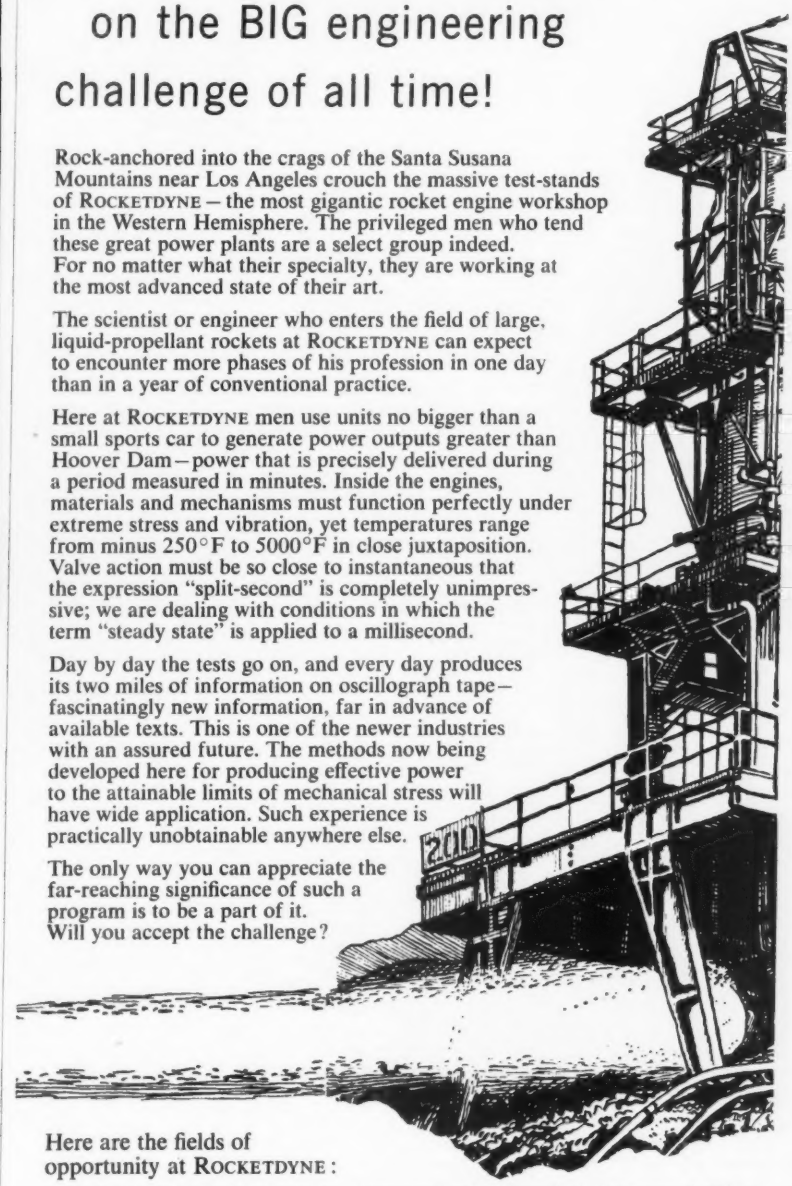

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Fuel control system for afterburner of turbojet power plant (2,739,442). Robert A. Neal and Bruce H. Pauly, Holmes, Pa., assignors to Westinghouse Electric Corp.

Venturi responsive to fuel pump output to establish a pressure differential, and a servomechanism responsive to fuel flow rate for operating a fuel supply control valve.

Cold blast jet engine (2,739,443). Samuel E. Bohrer, Long Beach, Calif.

Nacelle with openings communicating with an annular air passage. Openings admit cooling air to the engine, the air passing around a baffle after traversing the engine and moving into the nacelle.

Ramjet fuel distribution device (2,739,444). John Chamberlain, Manchester, Conn., assignor to United Aircraft Corp.

Device responsive to the Mach number of the stream flowing through the ramjet for regulating fuel injection into the combustion chamber. A pressure ratio sensing device is located adjacent to a flame spreader downstream of the fuel injector.

Compound aircraft propelling ramjet and pulse jet engine (2,740,254). Alb C. Ballaver, Elbert R. Sargent, and James H. Schmidt, Kirkwood, Mo., assignors to McDonnell Aircraft Corp.

Pulse jet disposed within a ramjet combustion chamber. Fuel supplied to the ramjet is fired by the exhaust stream issuing from the pulse jet exhaust tube.

Rotor blade mounted jet engine (2,740,482). Stanley Hiller, Jr., and Harold H. Sigler, San Carlos, Calif., assignors to Hiller Helicopters.

Ramjet mounted on the tip of a rotor blade with a metal bracket. Engine has a fuel supply leading from the blade.

Propellant composition (2,740,702). Harry W. Mace, Glendale, Calif., assignor to Aerojet-General Corp.

Ammonium perchlorate-asphalt base propellant for jet propulsion motors containing about 1% to 4% by weight of a catalytic compound composed of chromium sesquioxide and a metal oxide selected from the group consisting of ZnO, Fe_3O_4, SnO_2, TiO_2, Al_2O_3, and CuO, the amount of the metal oxide being up to about 50% by weight of the mixture.

Process for producing globular propellant powder grains (2,740,704). John J. O'Neill, Jr., and Gilbert R. Cox, Norwalk, Conn., assignors to Olin Mathieson Chemical Corp.

Process of making grains having a diameter of at least 0.025 in. Bodies of propellant powder base lacquer are presized and suspended in a nonsolvent medium. Reduced viscosity of the lacquer is maintained until the bodies approach spherical shape, and then are hardened.

Compressor temperature sensing device (2,741,919). Arthur W. Gaubatz, Indianapolis, Ind., assignor to General Motors Corp.

A portion of air within the stator casing of an axial flow compressor is recirculated and passed over a sensing means for measurement of temperature.

Process for preparing composite propellants (2,742,672). Charles A. Thomas, Dayton, Ohio, assignor to the Secretary of War.

Fuel mixture for jet engines, cold molded and cured at a temperature below 80 C. Contains equal parts of sodium nitrate and ammonium picrate and 5 to 10% (by weight) of a liquid thermosetting synthetic resin.

Fuel system for pilot burners of gas turbine engines reheat equipment (2,742,755). David Omri Davies, Charles Gordon Morley, and William Ralph C. Ivens, Derby, England, assignors to Rolls-Royce Ltd.

Automatic scheduling of an air/fuel mixture in the afterburner of a turbojet power plant. A pressure-responsive device varies the air supply under pressure, insuring metered flow of fuel from pump to afterburner.

Temperature measurement and override control for turbojet engines (2,742,756). Deslonde R. de Boisblanc, Bartlesville, Okla., assignor to Phillips Petroleum Co.

Combined thermocouple and flame detector. The amount of fuel supplied to the injector is automatically decreased when the electric output in the detector assumes a predetermined characteristic value.

Starter control system (2,742,757). John S. Jaquith, Cedar Grove, N. J., assignor to Bendix Aviation Corp.

Means for initially opening air and fuel controls to supply the combustion chamber. Air and fuel controls close when fluid pressure drops below a predetermined value.

Starter control system (2,742,758). Jack J. Kelly, Waldwick, N. J., assignor to Bendix Aviation Corp.

Control and auxiliary circuits for initially energizing air, fuel, and ignition systems. When fluid pressure drops below a predetermined value, a shunt circuit energizes the system.

Starter control system (2,742,759). Cameron D. Flanigen and William J. Dietz, Jr., Hillside, N. J., assignors to Bendix Aviation Corp.

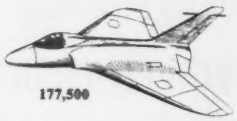
When a rise in temperature exceeds a predetermined value, pressure responsive means de-energizes the ignition system. Starting cycle is terminated upon a decrease in pressure due to depletion of starting fuel.

Controlled area combustion for ramjet (2,742,761). James W. Mullen II, Richmond, Va., assignor to the U. S. Navy.

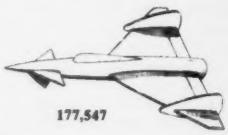
Fuel injection within a shroud spaced from the inner wall of a combustion chamber. A second injector supplies fuel only in the space between the shroud and the inner wall of the chamber. Fuel is regulated to supply one injector to the exclusion of the other.

Combustion chamber for axial flow gas turbines (2,742,762). Malcolm S. Kuhring, Ottawa, Canada, assignor to National Research Council.

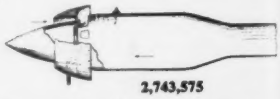
Tubular inserts surrounding fuel inlets provide passages for primary air into the combustion chamber. The air stream projected into the chamber prevents build-up of carbon deposits around the inner extremities of the passages. Deposits are confined to the space surrounding the airstream and do not tend to restrict airstream flow.



Airplane (design) 177,500. Edward H. Heinemann and Leo J. Devlin, Los Angeles, Calif., assignors to Douglas Aircraft Co., Inc.

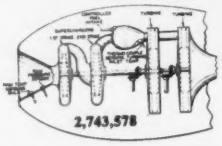


Airplane (design) 177,547. Lian-Tong Wen, New York, N. Y., assignor one-third to Alfred W. Vibber, Ridgewood, N. J.



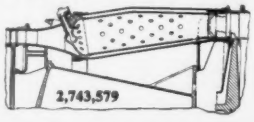
Valveless intermittent combustor with automatic flow control (2,743,575). Witold B. Brzozowski, Montreal-Outremont, Quebec, Canada.

Entrance passage admits air into and withholds air from a combustor tube. Shoulder openings channel air into the tube from the entrance and direct combustion products from the tube against the exhaust passage for propulsive expulsion.



Turbojet engine control system (2,743,578). Edward J. Hazen, Westwood, N. J., assignor to Bendix Aviation Corp.

System for determining the maximum permissible operating temperature. Control voltages are derived in response to air intake temperature and turbine speed.



Gas turbine engine with turbine nozzle cooled by combustion chamber jacket air (2,743,579). Arthur W. Gaubatz, Indianapolis, Ind., assignor to General Motors Corp.

Discharge ends of flame tubes are mounted on nozzle shrouds. A passage for cooling air is provided through struts disposed at the discharge ends of the flame tubes.

Igniter for rocket motors (2,743,580). Sidney Loeb, Los Angeles, Calif., assignor to Hughes Aircraft Co.

Squibs within a roll of ignitable material bonded to a sheet of cellulose acetate. The squibs are burned at a desired instant to ignite the solid propellant material.

EDITOR'S NOTE: The patents listed above were selected from recent issues of the Official Gazette of the U. S. Patent Office. Printed copies of patents may be obtained at a cost of 25 cents each from the Commissioner of Patents, Washington 25, D. C.

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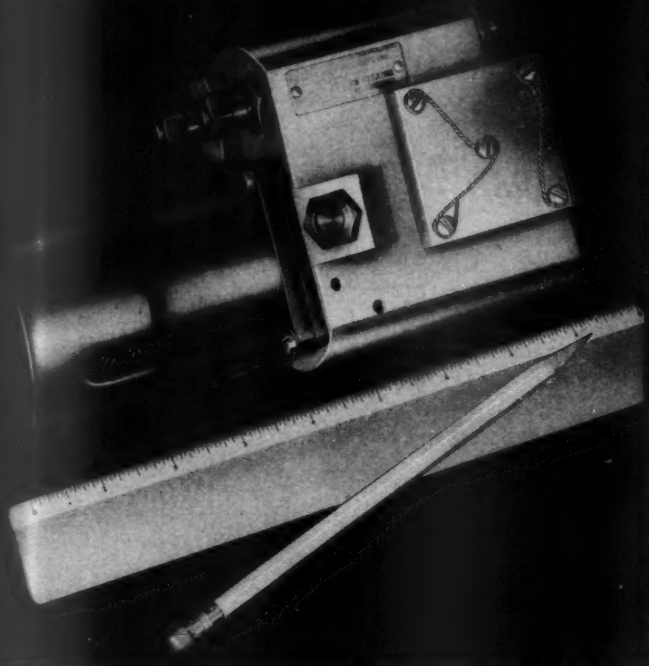

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Pressure range from 0 to 1500 PSIG with compatible flow.

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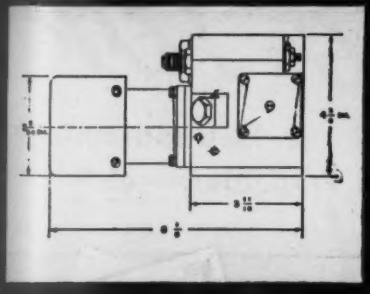
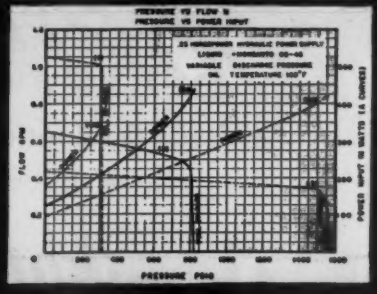
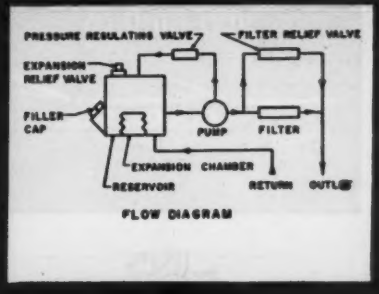
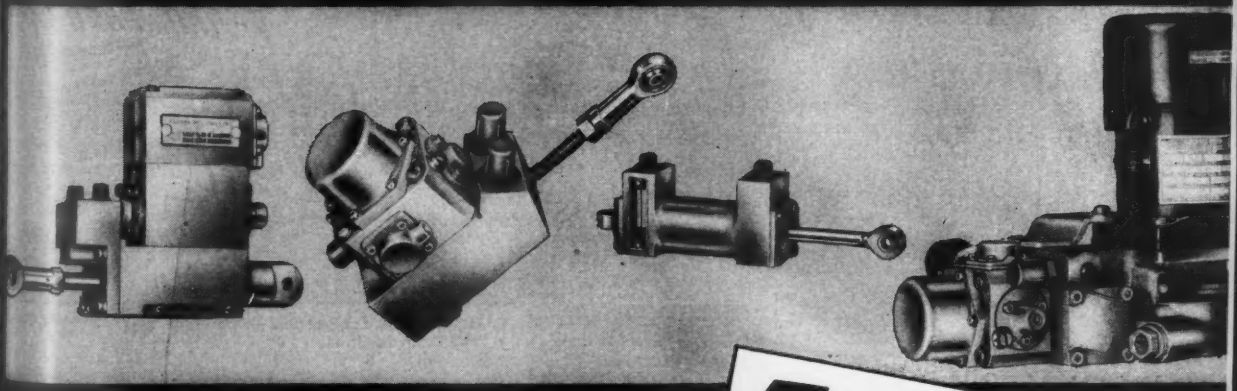






FLOW DIAGRAM



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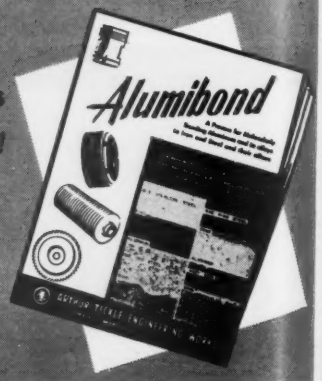

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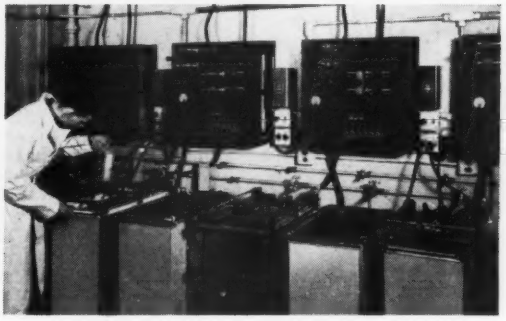

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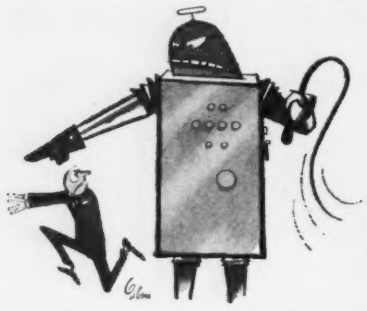

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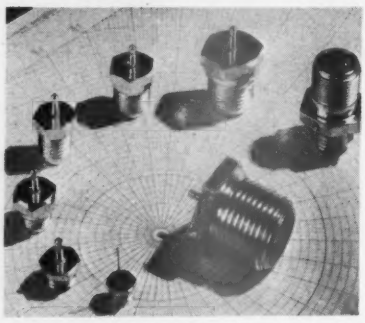
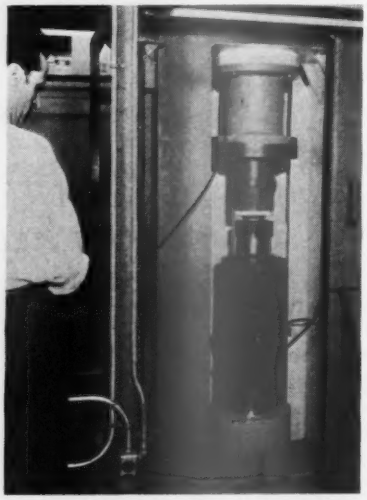


Pressure-Tight Squibs. Standard units include 13 types of squibs, igniters, and explosive packs. Welded double-bridge wires. McCormick Selph Associates, 62 Hollister Airport, Hollister, Calif. (photo).

Power Supplies. Lightweight (6 oz), compact (4 cu in.), transistorized dc to d-c units for missile use. Up to 10 w output. Universal Atomics Corp., 48 St., New York 17, N. Y.

Induction Resolver. Size 11 has total functional error of 0.05% for missile guidance systems. Diehl Mfg. Co., Finderne Plant, Somerville, N. J.



Large Load Cell. SR-4 has 250,000-lb capacity, 22 in. high, and 12 in. diam to measure rocket thrust. Accuracy of 0.1%. Baldwin-Lima-Hamilton Corp., Philadelphia 42, Pa. (photo).

Mechanical

Dies. Tu-Bend plastic dies for bending metal tubing. Warren Plastics & Engineering, 27500 Groesbeck, Roseville, Mich.

Rocket Power Unit. Solid propellant auxiliary APU-1 weighs 29 lb, delivers 65 w or 2.5 hp for 1 min. For missile use. AiResearch Corp., Los Angeles 45, Calif.

Turbo-Starter. Liquid monofuel (isopropyl nitrate) plus cordite has dry weight of 85 lb. British Thomson-Houston Co., Alma St., Coventry, England.

Superpressure Equipment. For pressures to 100,000 psi and temp to 1000 F. Pressure vessels, valves, fittings, etc. Superpressure Div., American Instrument Co., Silver Spring, Md.

Chemicals

High Temp Insulation. Castable Alundum 33-I protects up to 3300 F. Norton Co., Refractories Div., Worcester 6, Mass.

Silicone Rubber. Improved shrink, low toxicity, improved cure. Designated SE-361, SE-371, and SE-381. Silicone Products Dept., General Electric Co., Waterford, N. Y.

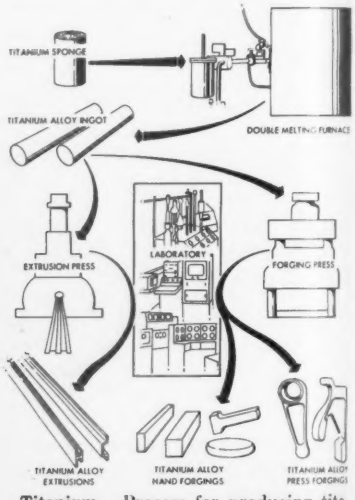
Unsym-Dimethylhydrazine. Storage and handling properties. Westvaco Chlor-Alkali, South Charleston 3, W. Va.

Test

Altitude Simulation Chamber. 64 cu ft with range of −100 to 500 F. American Research Corp., 11 Brook St., Bristol, Conn.

Missile Tracking Camera. Drive accuracy of 1½ millisec. 16- and 35-mm models. 10–40 frames per sec. Flight Research, Inc., Richmond, Va.

Processess



Titanium. Process for producing titanium press forgings and extrusions was revealed by Harvey Aluminum, 19200 S. Western, Torrance, Calif. (photo).

Xerography. Dry writing is a clean, fast, dry, electrostatic copying process with photo accuracy. Anything written, typed, drawn, or printed can be reproduced in a matter of minutes. The process requires neither water, liquid chemicals, or film negatives. The process is ideal for short run items such as printed circuits (photo). Haloid Corp., 2–20 Haloid St., Rochester, N. Y.

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Guided Missile Equipment

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(From editorial in first annual Guided Missile Equipment Supplement, JET PROPULSION, September, 1955)

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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

Boundary Layer Theory, by Hermann Schlichting, translated by J. Kestin, McGraw-Hill, New York; Pergamon, London; and Braun, Karlsruhe, 1955, 535 + xx pp. $15.

Reviewed by WALLACE D. HAYES
Princeton University

Boundary layer theory underlies the explanation of the effects of viscosity and of heat conduction as they influence most flow fields of practical interest. As such, this theory is a fundamental subject in the field of jet propulsion. It was in 1904 that Prandtl proposed the concept of the boundary layer, but despite extensive theoretical development no text devoted to the subject appeared until fairly recently. In 1938 a two-volume work under composite authorship appeared under the able editorship of S. Goldstein, which has served as a standard reference for many years. Not until 1951 did a single text presenting the subject to the engineer appear, when Professor Schlichting's "Grenzschichttheorie" was published. The present book is an English translation of this book by J. Kestin, with revisions by the author partly to bridge the gap of four years between the original and the translation.

The book has a very comprehensive scope. The first few chapters are devoted to a general introduction and to the Navier-Stokes equations. Succeeding chapters develop the classical laminar boundary layer theory, including the theory of three-dimensional, of nonsteady, of suction, of thermal, and of compressible boundary layers. The remainder (about 40 per cent) of the book is primarily devoted to turbulent flow and turbulent boundary layers. The presentation of the material, though generally kept at a high scientific level, is made with the needs of the engineer in mind. Theoretical results are always examined in the light of experimental evidence. The bibliography, understandably weighted toward the German literature, is thorough and generally most adequate. The approach is primarily in the nature of an exposition and compilation. There appears to have been little or no attempt to discuss subtle and controversial points in the theory.

A couple of omissions were felt by the reviewer as minor weaknesses; these omissions are to a large extent explained by the effective date of 1951 for the book and by the publisher's limitations on size. Missing, for example, is the more recent work on three-dimensional laminar boundary layers of Howarth, Moore, Hayes, and others. Missing despite a rewrite of the chapter on compressible boundary layers is an exposition of the important Stewartson-Illingworth transformation and of the work based on it by C. B. Cohen and others. Missing is any mention of the phenomenologic theory of transition due to Emmons. In this latter respect, the author evidently considers the explanation of the phenomenon of transition by the small-disturbance stability theory as completely established. Despite the experimental confirmation of the predictions of the stability theory, the reviewer disagrees strongly. Three-dimensionality and nonlinearity are essential features of transition which find no place in the stability theory. Also, though the question is inconsequential in boundary layer theory, the reviewer regrets the author's assuming the Stokes relation in presenting the Navier-Stokes relations, ignoring the question of bulk viscosity.

Professor Schlichting's book fills an important void in the technical literature, and fills it with a well-conceived comprehensive work. It may be highly recommended as a basic text for the physicist or engineer.

Hydrogen Peroxide, by Walter C. Schumb, Charles N. Satterfield, and Ralph L. Wentworth, ACS Monograph no. 128, Reinhold Publishing Corp., New York, 1955, 759 pp. $18.50.

Reviewed by NOAH S. DAVIS
Becco Chemical Division
Food Machinery and Chemical Corp.

This monograph presents for the first time in English a comprehensive treatment on hydrogen peroxide. It contains information on the manufacturing processes, purification, structural materials, handling, physical and chemical properties, decomposition processes, stabilization, analytical procedures, and uses of hydrogen peroxide. An excellent subject and author index with more than 2500 references is included.

Although 80 per cent of the world production of hydrogen peroxide is now made by an electrolytic process, there are two organic processes, the auto-oxidation of anthroquinone and the oxidation of propane, which are of interest because they require little electrical power, and the authors believe that they may be more economical than the electrolytic processes. It has been shown that the purity of high strength hydrogen peroxide is essential for long-time storage prior to use for power generation. The electrolytic processes produce a very pure product which requires very little stabilization.

Structural materials are divided into four classes: from those that are suitable for long-time contact, to those that are not recommended for use with hydrogen peroxide. A table is included. Use of dissimilar metals in direct contact should be avoided to prevent electrolytic corrosion. Detailed methods for passivating compatible materials are given.

Hydrogen peroxide is classified as a "corrosive liquid" by the Interstate Commerce Commission. Drums and tank car shipments are permitted under a white label. Many studies have shown that

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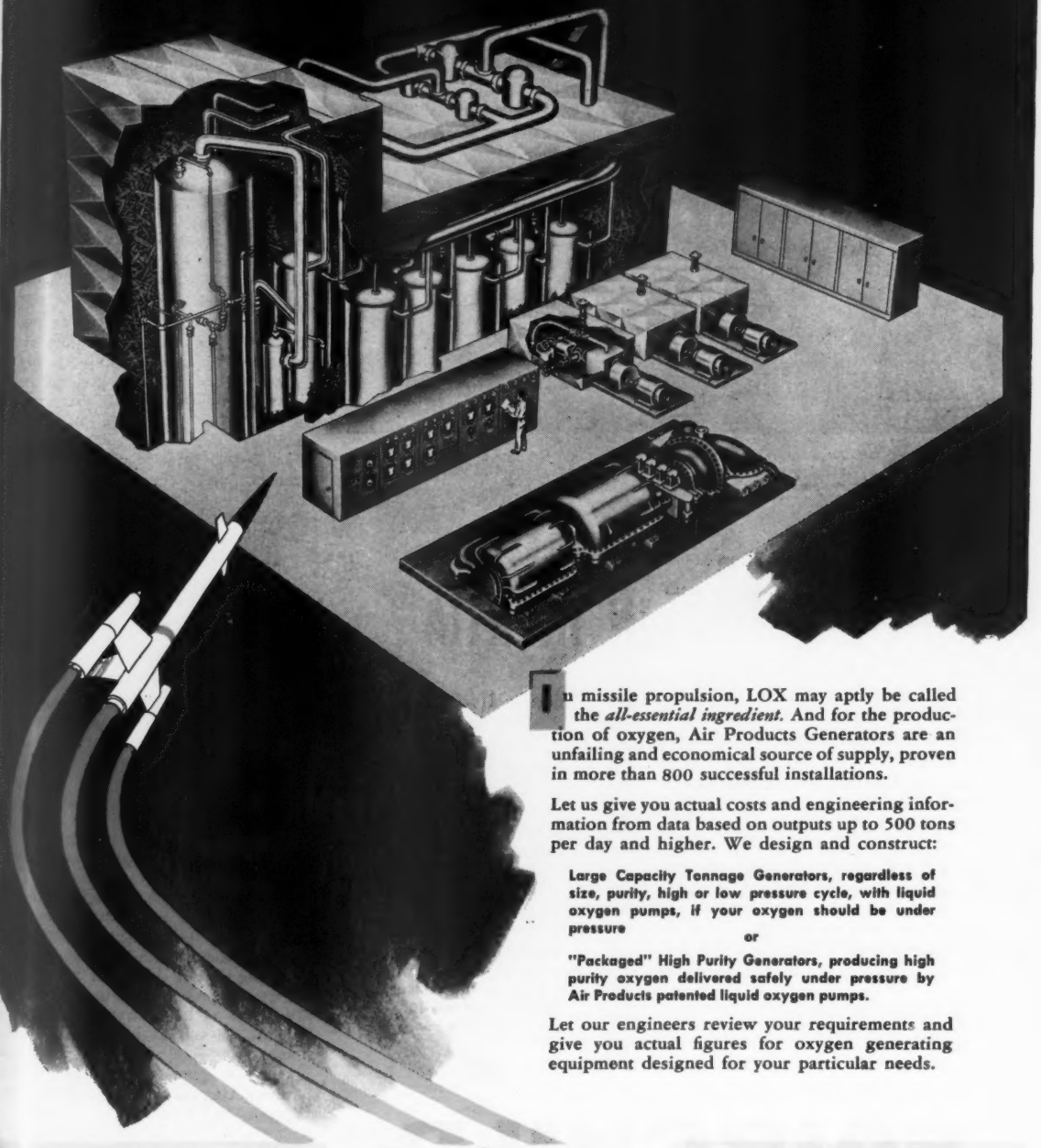

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ENGINEERING TIMETABLE

Dr. Mary Payne, Dr. Dmitri Olshevsky, Dr. LaVerne Philpott, are currently leading the development of inertial navigation systems at Fairchild Guided Missiles Division.

9:00 AM – DYNAMICS IN INERTIA

Under the direction of Dr. Olshevsky, a staff of outstanding scientists, including Dr. Payne and Dr. Philpott, is presently engaged in research and development of inertial navigation systems at Fairchild Guided Missiles Division.

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mechanical impact will not detonate 90 per cent hydrogen peroxide. The effect of powerful initiators, heavy confinement, high temperature, and higher strength hydrogen peroxide is discussed. The possibility of self-heating of drums and tanks has been calculated, and control measures to be taken are described. Data on possible vapor phase explosives are presented. The authors conclude that convection is sufficient to dissipate the heat of *normal* decomposition at ambient temperatures up to 150 F. The precautions important in handling hydrogen peroxide, including proper clothing and flushing of any spills with water, are enumerated.

The recommended physical and thermodynamic properties of hydrogen peroxide are given.

Both vapor phase and liquid phase decomposition of hydrogen peroxide are discussed. This reaction may be either homogeneous or heterogeneous depending on such things as temperature, pressure, and materials of the walls. A survey of the literature on the catalytic decomposition of hydrogen peroxide by the elements, according to their position in the periodic table, is given along with possible catalytic mechanisms and poisoning of catalysts.

Although pure hydrogen peroxide is a very stable substance, in its manufacture a small amount of stabilizer is added to protect against minor contamination. Details on the effect of surface temperature and pH are given. A survey of substances and procedures for stabilization is included along with considerable experimental data. Temperature and duration of storage as well as final end use must be considered before choosing the amount and chemical composition of the stabilizer.

Details of all of the quantitative methods for determining the hydrogen peroxide content of solutions are discussed with the accuracies to be expected. These include the methods for determining the low decomposition rates obtained when testing compatible materials.

Concentrated hydrogen peroxide may be used as a monopropellant or as an oxidant in a bipropellant system. The former is simpler, but develops a lower specific impulse. In the bipropellant system the hydrogen peroxide may first be decomposed and the fuel burnt in the hot gases or the two liquids may be reacted together without prior decomposition of the hydrogen peroxide. The latter is simpler, but may offer problems to insure ignition and smooth combustion. Hypergolic (self-igniting) fuels are discussed along with methods for determining ignition delay and "slug" starting. Data are presented on the heat of decomposition of concentrated hydrogen peroxide as well as information on liquid catalysts, solid catalysts, and catalyst chamber operating problems. Details of many German military applications are given.

The only inorganic peroxide that is of interest is potassium superoxide KO_2. This material reacts with the CO_2 and moisture in the breath to fix the CO_2 as K_2CO_3 and liberate oxygen. It might be employed in a manned rocket to rejuvenate the air within the vehicle.

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Technical Literature Digest

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Reservoir	Conn. across Htr.	Conn. across Htr.
Minimum heating time	3 minutes	3 minutes
Over-all length	7.25″ max.	4.375″ max.
Greatest diameter	2.56″ max.	1.56″ max.
Peak anode v. forward	16 kv max.	8.0 kv max.
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Average anode current	225 ma. max.	100 ma. max.
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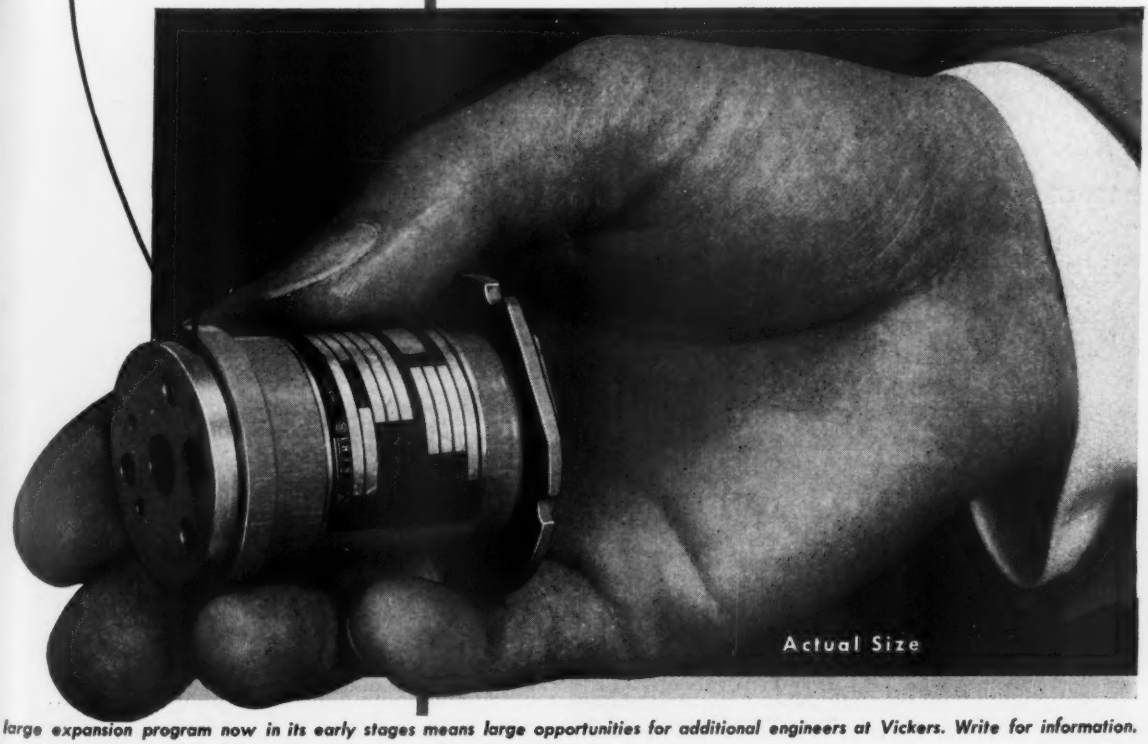

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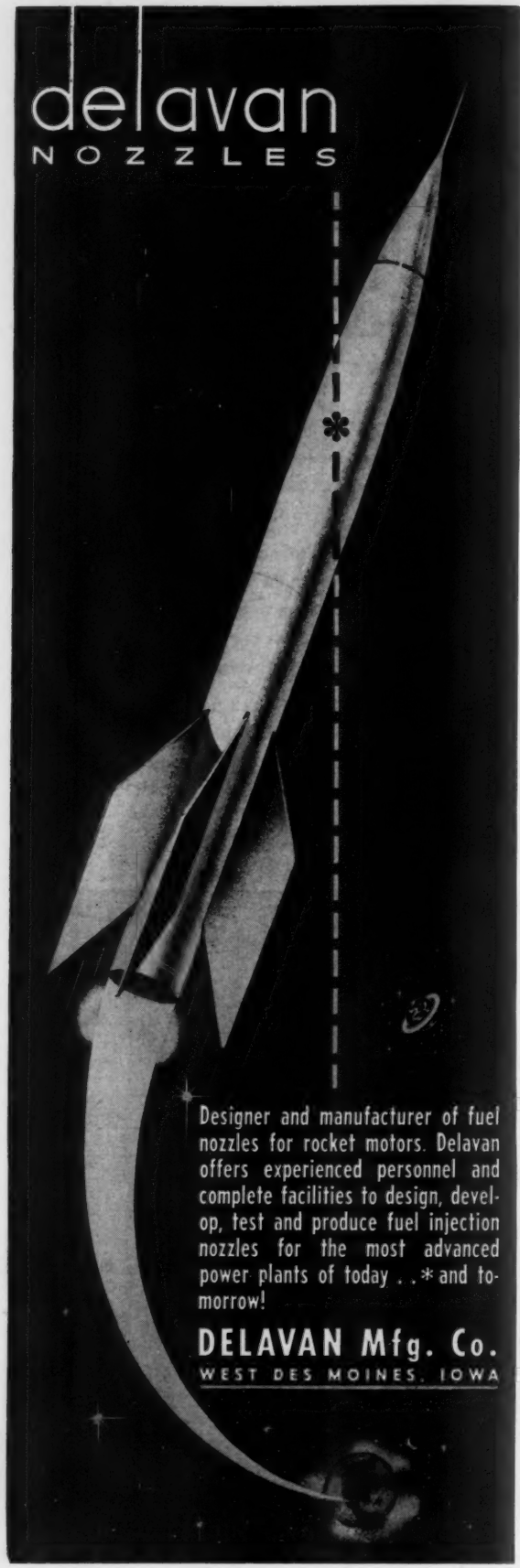
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J. Walter Thompson Co., Los Angeles, Calif.
DU PONT DE NEMOURS, E. I., AND COMPANY 626
Batten, Barton, Durstine & Osborn, New York, N. Y.
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Remsen Advertising Agency, Inc., New Haven, Conn.
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G. M. Basford Company, New York, N. Y.
THE GARRETT CORPORATION 700, 701
AIRESEARCH MANUFACTURING COMPANY
J. Walter Thompson Company, Los Angeles, Calif.
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G. M. Basford Company, New York, N. Y.
GENERAL ELECTRIC COMPANY, AGT DIVISION 687, 703
Deutsch & Shea, Inc., New York, N. Y.
GIANNINI, G. M., AND COMPANY, INCORPORATED 719
Grant Advertising, Inc., Hollywood, Calif.
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J. M. Mathes, Inc., New York, N. Y.
LOCKHEED AIRCRAFT COMPANY, MISSILE SYSTEMS DIVISION .. 636
Hal Stebbins, Inc., Los Angeles, Calif.
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Doyle, Kitchen & McCormick, Inc., New York, N. Y.
MARTIN, THE GLENN L., COMPANY 632, 683
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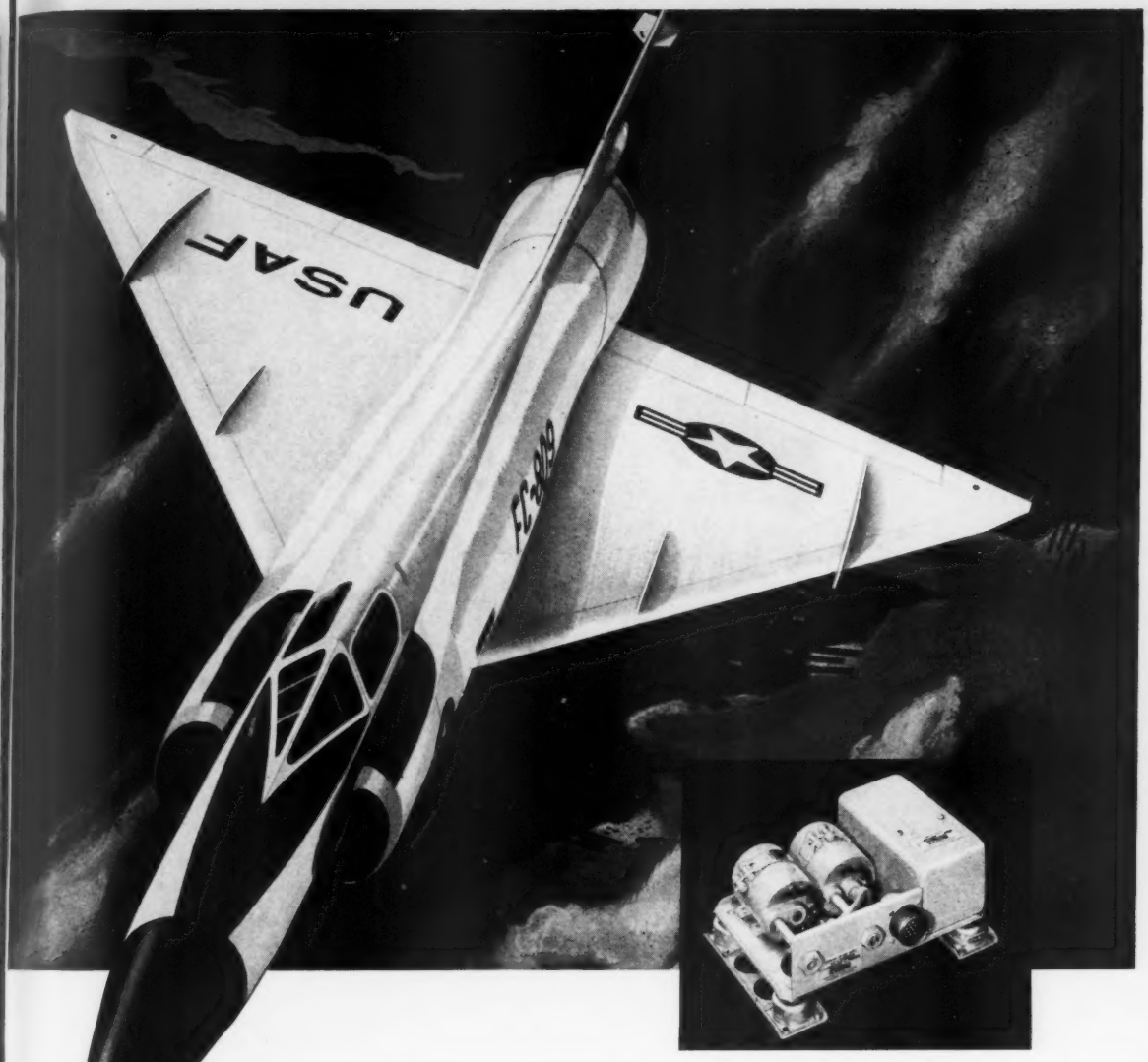

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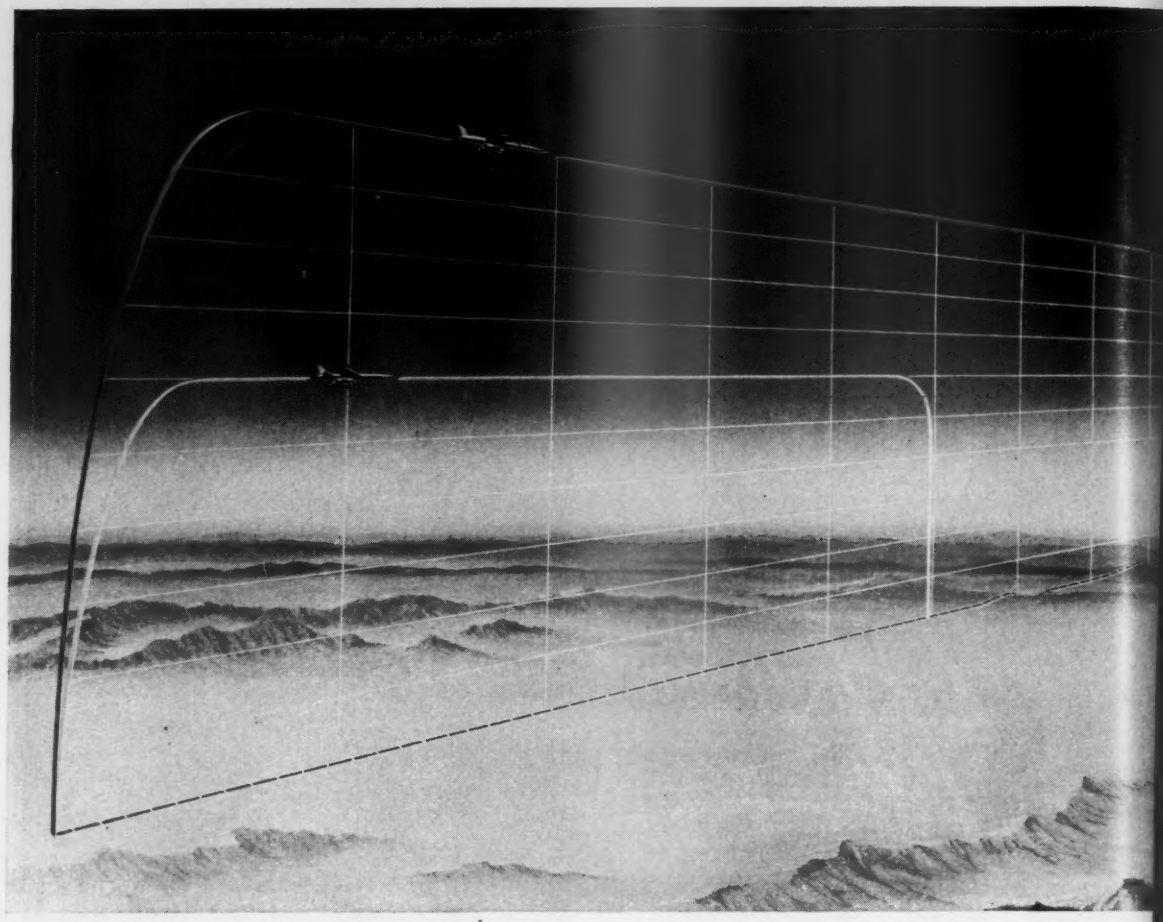

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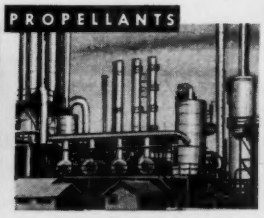
RAMJETS

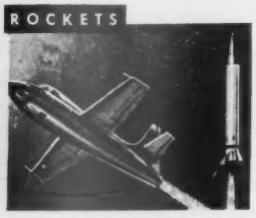
Marquardt Aircraft Company
Van Nuys, California

PROPELLANTS



Olin Mathieson Chemical Corporation
New York, New York

ROCKETS



Reaction Motors, Inc.
Denville, New Jersey

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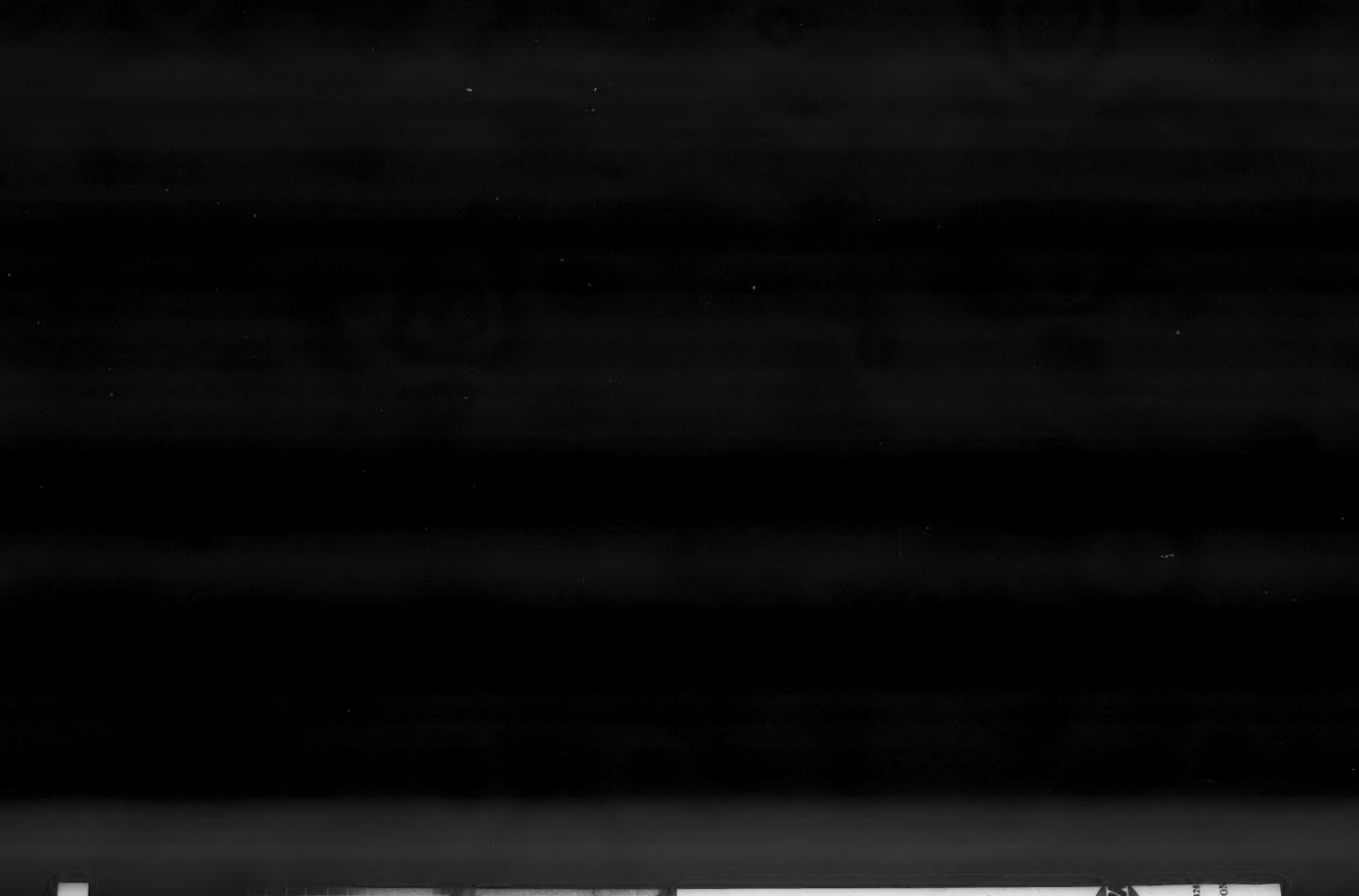
428